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SOLAR ENERGY

Solar Education for the 80's

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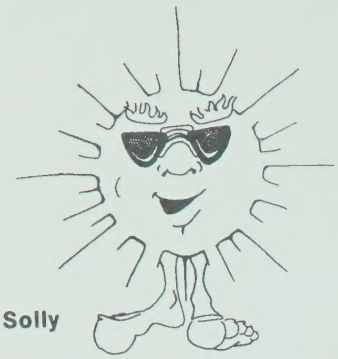

Solly

FOREWORD

When we selected solar energy as a special science topic for the classroom, we did not anticipate the overwhelming interest that would be generated. Initially, we sought an applied physics topic suitable for an elective unit. Solar energy seemed appropriate because it could be used as a vehicle to teach many of the principles of heat and light in an applied context. As teacher/students we proceeded to develope and teach the material now in your hands.

To the authors and students, solar energy turned out to be a very special context for learning physics. The physics was being learned but the principles of utilizing solar energy gradually gained emphasis. As we learned more about the topic of solar energy, we came to realize the much larger contexts within which the use of solar energy was embedded. We encountered and engaged in the debate over active solar systems versus passive systems. This debate led us to the realization of the dominance of a technology-oriented mindset in our society.

Active solar systems are given nearly all of the research grants, tax breaks and media attention. Most of the public hold a vision of pipes and special apparatus when solar homes are discussed. We hope to change this solar home vision to that of a well insulated home with a majority of windows facing south. Our personal biases at this moment favor passive solar systems. As an energy alternative, the passive system is not only the cost effective solar system (which is usually the major concern), but the passive system also makes it possible "to live lightly on the earth". As a bonus adopting passive solar energy put us in a position which encourages the critical examination of the mindset of society and of ourselves.

F.J.
H.vK.
G.K
J.K.

Notes:
We hope you interact with this book as strenuously as we have in the first two years of its evolution. We encourage you to write in it, change it, make it your own and use it to evolve your thinking and actions.

ACKNOWLEDGEMENTS

The authors of *Solar Energy: Solar Education for the 80s* are indebted to the students of Queen Elizabeth Composite High School, Edmonton, for their patience and enthusiasm. We appreciate the assistance and information supplied by the Solar Energy Project, National Research Council, Ottawa; the Atmospheric Environment Service, Fisheries and Environment Canada; the Solar Energy Project, U.S. Department of Energy and the Sun, Wind, Energy Research Project, Alberta Research Council. Thanks to the many individuals who expressed an interest in our project, to John LeBel of J.M. LeBel Enterprises Ltd. for supporting our publishing concepts, to KC Conroy for her endless hours of typesetting and layup-design. A special thanks goes to the families of the authors for their patience, support and understanding.

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SOLAR ENERGY

Solar Education for the 80s

Teacher — Authors

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Number of labs - 4; Number of figures - 94;
Number of exercises - 19; Number of questions - 140.

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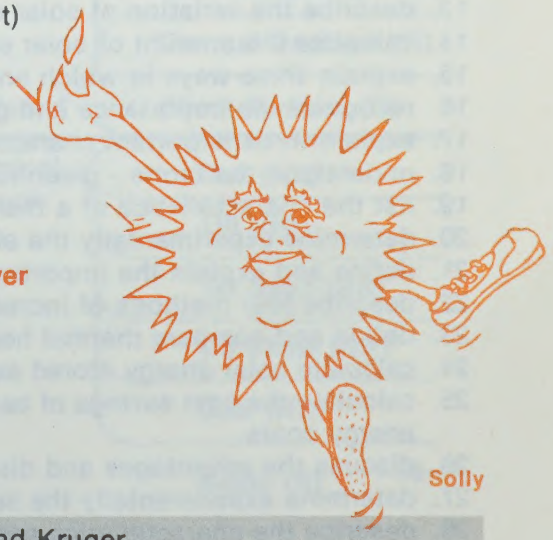

Solly

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Prerequisite Knowledge and Skills

Because of a possible wide variation in the background of students, the following list of prerequisite knowledge and skills is suggested but not absolutely necessary to successfully complete this unit on solar energy. For example, many of the terms required for this unit can be defined operationally without detailed theoretical derivation and explanation. The following list is arranged in order of decreasing importance.

1. Define and distinguish between temperature and heat energy.
2. Identify three methods of heat transfer - conduction, convection and radiation.
3. Explain qualitatively the principles of reflection, transmission, absorption and refraction of light.
4. Define and use the SI metric unit of energy - the joule (J).
5. Manipulate the SI metric prefixes.
6. Measure and calculate quantities with a correct number of significant digits.
7. Understand and distinguish the infrared, visible and ultraviolet regions of the electromagnetic spectrum.
8. Demonstrate basic graphing skills.
9. Do basic mass, volume and density calculations.
10. Do basic trigometric calculations.

Unit Objectives

Upon completion of this unit, the student should be able to:

1. recognize the importance of solar energy as an important component of present and future energy supply.
2. relate solar energy to other energy forms.
3. explain briefly the source of solar energy and its propagation through space.
4. identify several advantages and disadvantages of solar energy.
5. identify and arrange in the correct order the three major components of solar radiation striking the outer atmosphere.
6. calculate solar power and solar power per unit area from given data.
7. describe qualitatively the absorption, relection and transmission of solar energy in Earth's atmosphere.
8. define and use the terms solar altitude, solar azimuth and direct and diffuse solar radiation.
9. identify and describe the factors determining the solar energy per unit area on Earth's surface.
10. use the terms conduction, convection and radiation to explain heat transfer in or on each of the following: Earth's atmosphere and surface, passive solar dwellings and active solar systems.
11. describe the operation of a radiometer and a stroboscope.
12. determine experimentally the variation of solar radiation intensity.
13. describe the variation of solar energy intensity on a daily, monthly and yearly basis.
14. calculate the amount of solar energy on a surface from radiation data, surface area and time.
15. explain three ways in which entry of solar energy into a dwelling can be controlled.
16. recognize the importance and give examples of retrofitting.
17. explain three important characteristics of a low energy dwelling.
18. understand the terms - greenhouse effect and thermal mass.
19. list the characteristics of a thermal mass used for solar heat storage.
20. determine experimentally the effect of surface color on solar radiation absorption.
21. define and explain the importance of thermosiphons in passive systems.
22. describe four methods of increasing passive storage capacity.
23. define and compare thermal heat and latent heat of fusion.
24. calculate solar energy stored as heat using $h = vc \triangle t$ and $h = mL$.
25. calculate the cost savings of certain solar energy applications and relate to present and future energy costs.
26. discuss the advantages and disadvantages of different methods of heat storage.
27. determine experimentally the solar heat storage characteristcs of different substances.
28. describe the characteristics and operation of active air and liquid collectors and systems.
29. discuss the practical and economic problems associated with active systems.
30. define and compare active and passive solar systems.
31. recognize the immediate and long term advantages of passive versus active systems.
32. develop and independently complete a solar energy project.
33. describe the characteristics and give examples of concentrating solar collectors and solar cells.

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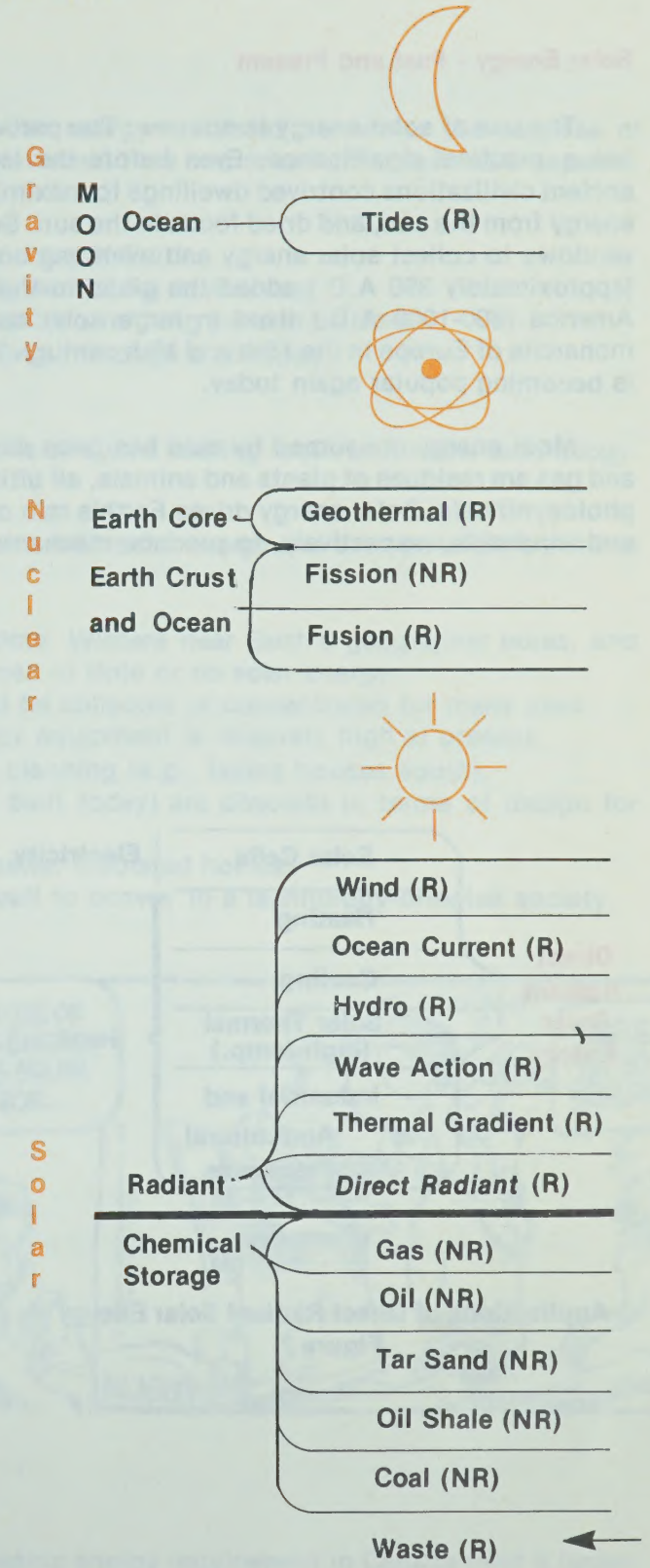
Energy Resources

An increasing concern is expressed by many individuals and groups about the growing demand for energy, the availability of present energy resources, and the enviromental effects of the development and use of energy resources. The expanded energy needs of a growing population together with a rise in the standard of living combine to produce an overall increase in demand for energy. The most readily available energy supplies on Earth are being used first, leaving the lower quality, hard to develop, or unfavorably located sources for later use.

The uncertainty of energy supply is well illustrated by events which are prominent in the daily news. Large energy projects rise and fall in priority. Energy prices change with shocking suddenness. There are conflicting reports of the extent of energy reserves. In addition, the increasing use of fossil fuels such as coal, petroleum and natural gas as raw materials for producing many important petrochemical products reduces the amount of fossil fuels available for direct energy production.

Environmental effects related to the development and use of energy resources are a matter of great concern to many special interest groups. There are those who wish to preserve the environment at any cost and at the other end of the spectrum, there are those who argue that the continued growth in energy use takes priority.

Concern and uncertainty stimulate the search for alternatives to present energy sources. It is unlikely and perhaps undesirable that energy demand will level off as a result of conservation methods, zero population growth and changes in lifestyle. With the possible exception of nuclear fusion, it is also unlikely that a new source of energy will completely supply all future energy needs. The most likely scenario will involve a *diversification* of energy resources to include *many* of the renewable energy sources to be found in Figure 1. For many reasons discussed in this unit, solar energy is likely to become an increasingly important resource-*component* of the world's energy supply. The solar component in Figure 1 to which this unit addresses itself is the renewable resource, *direct radiant.*

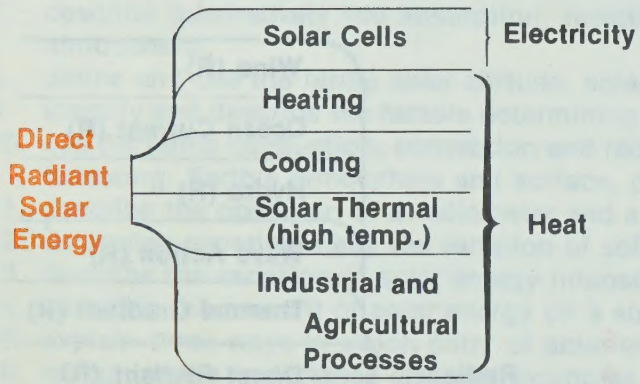


Energy Sources
(Nonrenewable (NR) Renewable (R))
Figure 1

Solar Energy - Past and Present

The use of solar energy is not new. The particular prominence of the sun in ancient mythology has a practical significance. Even before the legendary Prometheus "stole the fire of heaven", ancient civilizations contrived dwellings to maximize the use of solar energy, grew plants that stored energy from the sun, and dried foods in the sun. Socrates (470-399 B.C.) recommended south-facing windows to collect solar energy and overhang on the windows for summer shading. The Romans (approximately 350 A.D.) added the glass to these solar windows. The Navaho Indians of North America (800-1000 A.D.) lived in large solar caverns. Greenhouses were made popular by the monarchs of Europe in the 15th and 16th century. Wood stoves were used for auxiliary heat much as is becoming popular again today.

Most energy consumed by man has been directly or indirectly produced by the sun. Coal, oil and gas are residues of plants and animals, all ultimately owing their energy to solar energy through photosynthesis. Solar energy drives Earth's rain cycle and winds which power hydroelectric plants and windmills, respectively, to produce mechanical and then electrical energy.



Applications of Direct Radiant Solar Energy
Figure 2

Today solar energy is directly used in many different applications and can be used in many other applications as shown in Figure 2. The sun illuminates and heats many buildings, heats water for domestic use, generates electricity using solar cells in remote locations (such as space and uninhabited parts of the earth) and distills seawater to produce fresh water for drinking and agriculture. Solar furnaces which concentrate the sun's energy are presently being used to manufacture clay bricks in parts of the world where solar energy is plentiful but building materials are scarce.

The important point regarding solar energy is that its use is realistic *now* and the knowledge for widespread use is available *now*. Countries such as Japan and Israel have utilized solar energy for heating water and for space heating for many years. Across North America, solar energy societies, government agencies, private industry, contractors, architects and private individuals are becoming more involved with solar energy utilization. The major obstacle at present is a public lack of knowledge and awareness of what solar energy can do now and in the future.

Advantages of Solar Energy

The most readily observed advantages of solar energy are listed below for the purpose of orientation. Later study will amplify the points presented here and reveal other favorable aspects.

1. Solar energy is available in large amounts.
2. Solar energy is widely distributed over the surface of Earth.
3. Solar energy is renewable. Tomorrow's supply cannot be used today.
4. Solar energy is relatively constant and predictable over long periods of time.
5. Solar energy can be collected inexpensively (e.g., through a window).
6. Solar energy does not pollute.
7. Solar energy is free.
8. Solar energy in the most promising applications of space heating requires no new technology.

Disadvantages of Solar Energy

It is advisable to consider some of the problems with solar energy and their possible solutions before pursuing the study of present practices.

1. The supply of solar energy is variable with time. Winters near Earth's geographic poles, and nights and cloudy days in any region, are times of little or no solar energy.
2. Solar energy is dilute or spread out and must be collected or concentrated for many uses.
3. The capital cost of some kinds of solar energy equipment is relatively high at present.
4. Many uses of solar energy require long term planning (e.g., facing houses south).
5. Most current houses (including those being built today) are obsolete in terms of design for collecting solar energy.
6. In very cold climates solar heating requires better insulated homes.
7. The simplicity of solar space heating is difficult to convey to a technology-oriented society.

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Solar Energy is Now

An estimated 12% of the residential space heating energy requirement in Canada (and a larger percentage in the U.S.) is provided today by solar energy. This benefit is largely provided by accident as the result of putting windows in a house for internal and external vision. Greater than 50% of the residential space lighting requirements is provided by solar energy. Slowly the recognition of this lucky accident is spreading through our energy deficient world. A conscious effort to use solar energy is now evolving.

1. Most of the energy used in the world is produced from the combustion of fossil fuels. Explain how these fossil fuels are an indirect source of solar energy.

2. The use of solar energy can be classified into either direct or indirect uses. List three examples of each.

Direct Use	Indirect Use

3. Could the direct use of solar energy displace completely all other sources of energy? Explain.

4. How does mass production affect the cost of a manufactured item? (Consider what it would cost to produce *one* automobile from raw materials if no others were to be produced in the same way.) Comment on how this relates to solar energy equipment and solar designed homes.

5. Adapting construction techniques for new buildings of the solar age will be relatively easy, but what about existing buildings? Would it be energy efficient to demolish old public buildings, homes, or greenhouses (no matter what their age) and rebuild them in a manner which would make maximum use of solar energy? What should be done in this regard? Explain.

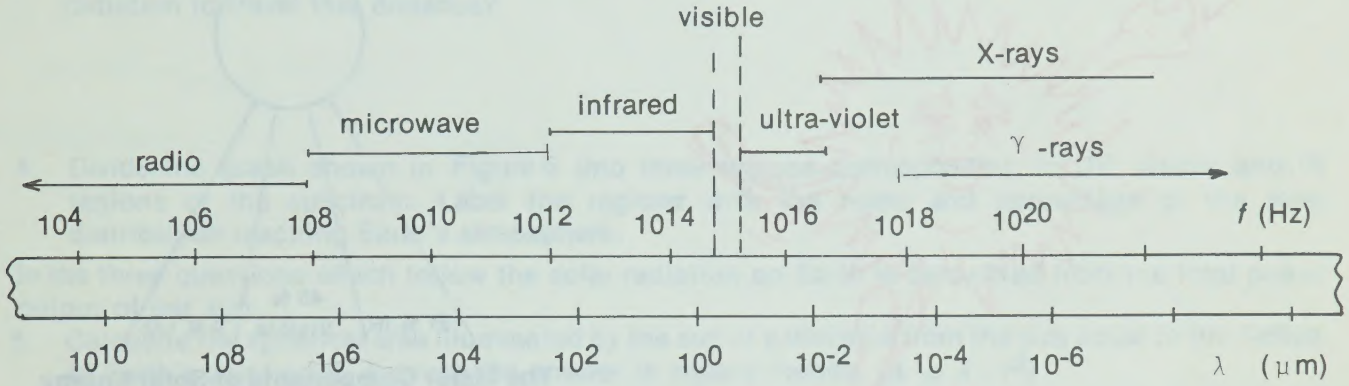
6. Discuss the statement, "solar energy is free and nonpolluting".

7. What political, economic, social and scientific factors affect the increased utilization of solar energy?

Energy from the Sun

The sun is a typical star constantly emitting energy as the result of nuclear fusion reactions. This energy is given off when the sun converts about 1.3×10^{17} kg/a of its mass to radiant energy which is emitted equally in all directions in space. The sun's power output of 3.9×10^{23} kW is essentially constant, varying by less than 5% over long periods of time. By comparison, to run all the factories, machines and vehicles and to heat all buildings on Earth requires about 5×10^{13} kW.

The sun emits energy in the form of electromagnetic radiation. This radiation is a wave consisting of oscillating electric and magnetic fields travelling at a constant speed of 3.00×10^{8} m/s The fundamental difference between the various kinds of electromagnetic waves is their wavelength (λ). The electromagnetic spectrum is a continuous range of radiation extending from gamma (γ) rays (very small wavelength, λ) to visible light, to radion waves (very large wavelength, γ.) (See Figure 3.) The names for the different kinds of radiation are historical and the boundaries are somewhat arbitrary.



The Electromagnetic Spectrum
Figure 3

Ultraviolet radiation, which causes sunburn and skin cancer, is sometimes called *black light* because it cannot be seen. *Infrared radiation* is often called heat radiation and can be felt, but not seen. The region between these two types is called the *visible region* of the electromagnetic spectrum because this region is the only part of the electromagnetic spectrum to which the human eye responds.

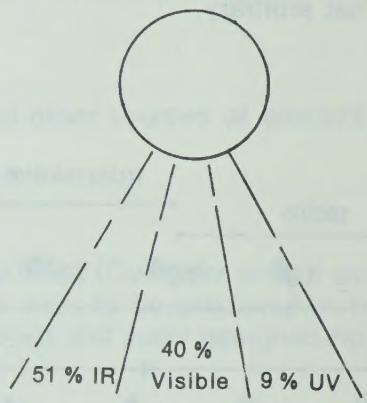
Table 1
UV, Visible and IR Regions of the Electromagnetic Spectrum

Region of the Electromagnetic Spectrum	Wavelength (λ) (μm)	Frequency (f) (x 10^{15} Hz)	Approximate Percentages (%)
Ultraviolet	0.20 to 0.40	1.5 to 0.75	9
Visible (violet to red)	0.40 to 0.70	0.75 to 0.43	40
Infrared	0.70 to 1.0×10^{2}	0.43 to 0.0030	51

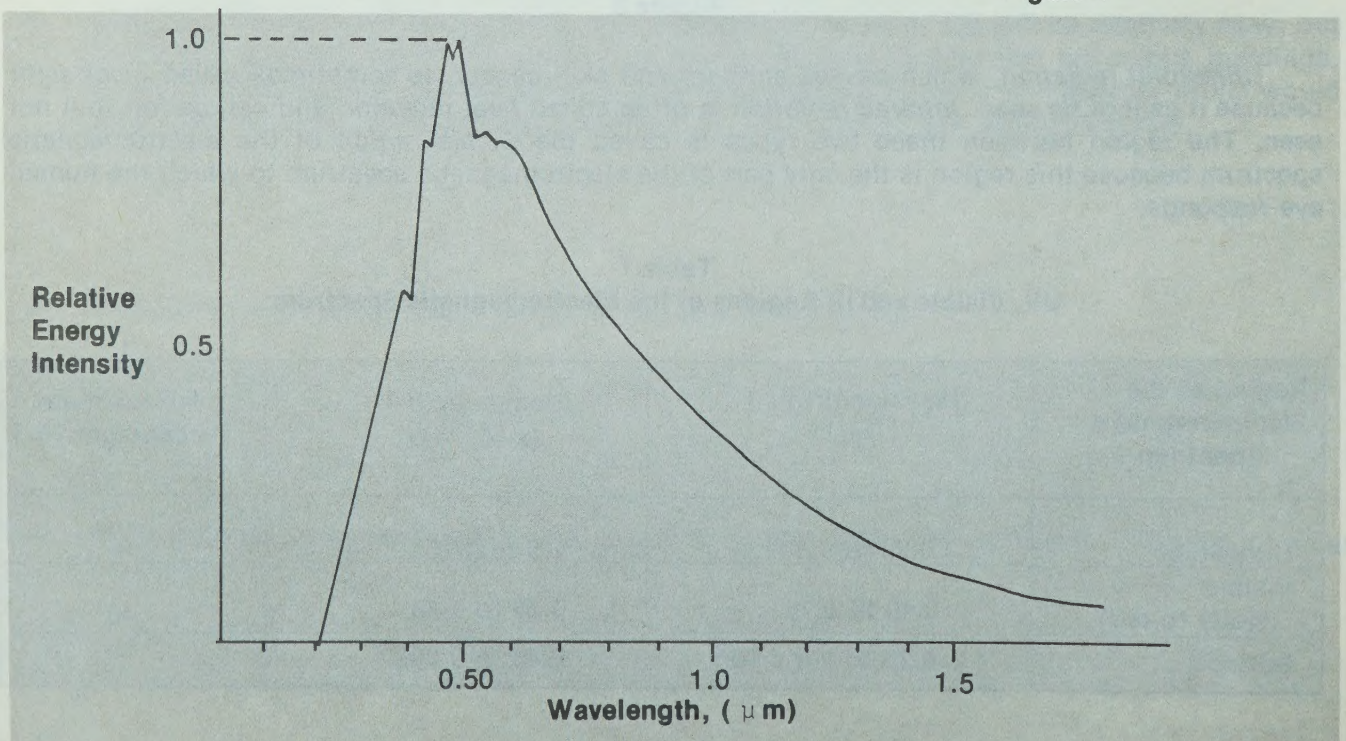
Solar Radiation Reaching Earth's Atmosphere

The illumination by the sun decreases as the distance from the sun increases. Specifically, the intensity of illumination is inversely proportional to the square of the distance from the sun (inverse square law). At a distance of 1.50×10^8 km, Earth receives and collects only a very small fraction of the sun's power output. However, this small fraction is very significant when compared to the energy demands on Earth. For example, the amount of solar energy falling on North America alone in one minute is more than enough to supply North America's total energy needs for one day.

Most of the solar radiation striking the outer atmosphere occupies the spectrum from about 0.20 to 3.4 μm. A typical energy distribution would be 9% ultraviolet, 40% visible and 51% infrared.



The Major Components of Solar Energy Reaching the Upper Atmosphere
Figure 4



Spectral Distribution of Direct Solar Radiation Reaching the Upper Atmosphere
Figure 5

Exercise:

1. If 3.9×10^{25} kg of the sun's mass can be converted to energy until it becomes a red giant, what would be the expected lifetime of the sun as we know it?

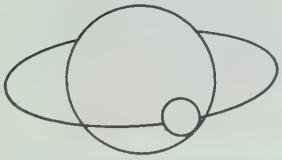
2. What information about the shape of Earth's orbit can be deduced from the fact that Earth receives a nearly constant intensity of solar radiation? How does this deduction compare to the actual shape of Earth's orbit?

3. The mean distance from Earth to the sun is 1.50×10^{8} km. How long does it take the solar radiation to travel this distance?

4. Divide the graph shown in Figure 5 into three regions corresponding to UV, visible and IR regions of the spectrum. Label the regions with the name and percentage of the total distribution reaching Earth's atmosphere.

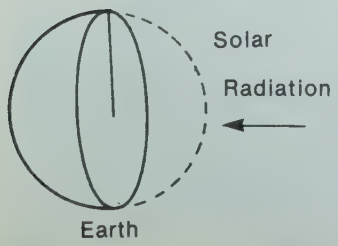
In the three questions which follow the solar radiation on Earth is calculated from the total power output of our sun.

5. Calculate the spherical area illuminated by the sun at a distance from the sun equal to the radius of Earth's solar orbit. Express the answer in square metres. [$A = 4 \pi r^2$]



6. Using the total radiation power output of the sun in kilowatts and the illuminated area in square metres from Question 5 calculate the average solar radiation power per unit area in kilowatts per square metre reaching Earth's outer atmosphere. The radiation power per unit area is called the *solar constant.*

7. Calculate the total solar radiation power falling on Earth's outer atmosphere in kilowatts. (The illuminated area of the day side of Earth can be assumed to be an area equal to the cross sectional area [A] of Earth.) [$A = \pi r^2$]

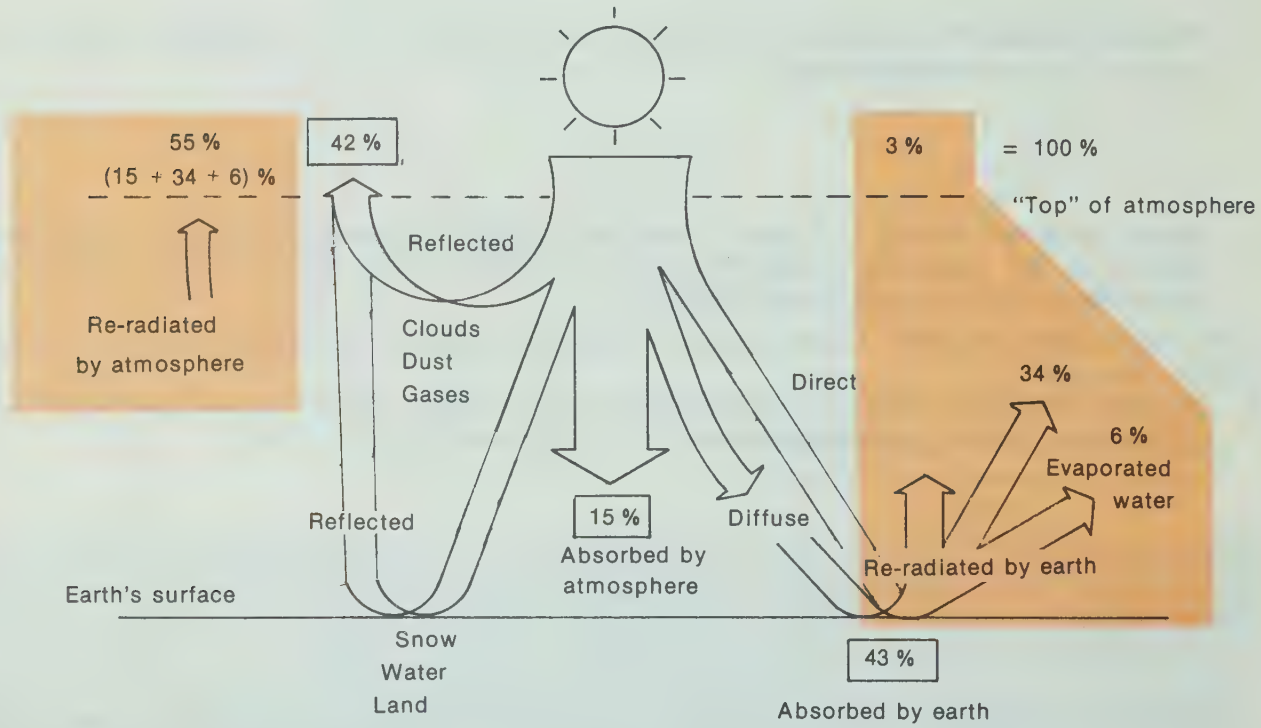


Atmospheric Absorption, Reflection and Transmission of Solar Radiation

Earth's atmosphere acts as a boundary for the solar radiation travelling through space. (Figure 5 shows the solar radiation incident on the outside of Earth's atmosphere.) When radiation travels through a surface or boundary three processes occur - absorption, reflection and transmission. The percentage of each process depends on the particular surface or boundary.

1. Variation of Solar Radiation Due to the Composition of the Atmosphere

The effects of the atmosphere and Earth's surface on the absorption and reflection of radiation are summarized in Figure 6 below. The percentages are approximate and represent an average solar altitude. Notice that for the purposes of Figure 6 no solar radiation energy is stored on Earth. The very small percentage stored in plants is neglected because it is recycled as plants die and decay.



The total incoming equals the total outgoing (i.e., 100 %).

Solar Energy Cycle
Figure 6

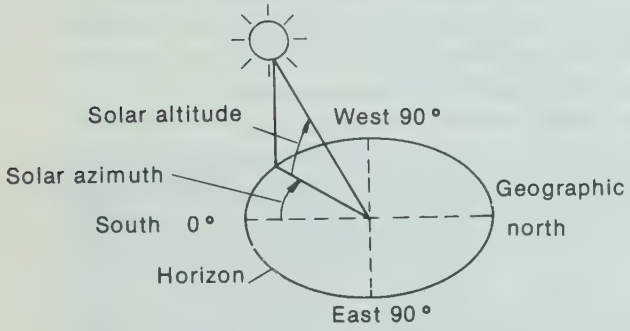
An important and complicated factor regarding the utilization of solar energy is the atmospheric boundary. Table 2 below summarizes some of the ways in which the solar radiation may be altered in composition and in intensity as the radiation passes through the atmosphere.

Table 2
Absorption and Reflection in Earth's Atmosphere

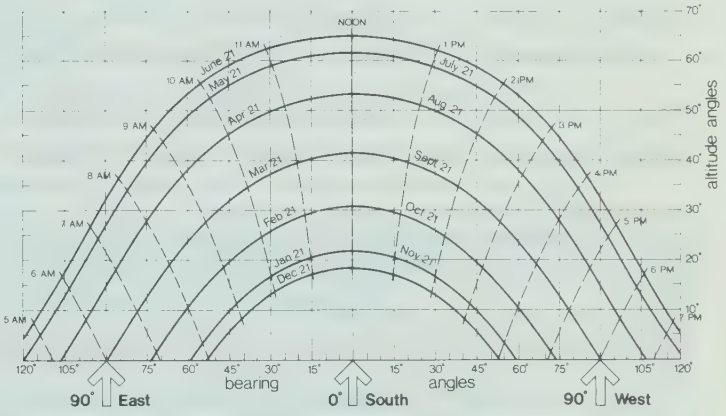
Process	Radiation Type	Location and Cause of Absorption and Reflection
Absorption	UV	- upper atmosphere by ozone, oxygen, nitrogen
	Red and IR	- throughout atmosphere by carbon dioxide and water
Reflection	primarily visible	- lower layers of the atmosphere by clouds - throughout atmosphere by dust particles

2. Variation of Solar Radiation Due to the Pathlength through the Atmosphere

In addition to the composition of the atmosphere, which is variable, the distance travelled through the atmosphere also affects the amount of solar radiation that reaches Earth's surface. The distance that the solar radiation travels through the atmosphere varies with the apparent position of the sun in the sky. Two angles are used to tell the sun's position. The *solar altitude* is the angular *height* of the sun in the sky. The solar *azimuth* is the angular *direction* to a point on the horizon directly below the sun. Solar azimuth is an angle measured east or west from south (0°). Figure 7 shows solar altitude and solar azimuth in diagram form. The solar altitude is the more important of the two variables and determines the pathlength and thus the absorption and reflection of solar radiation by the atmosphere.

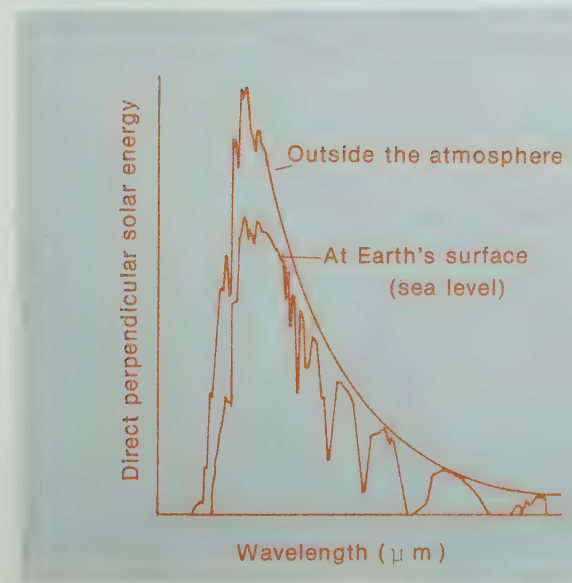


Solar Altitude and Azimuth
Figure 7

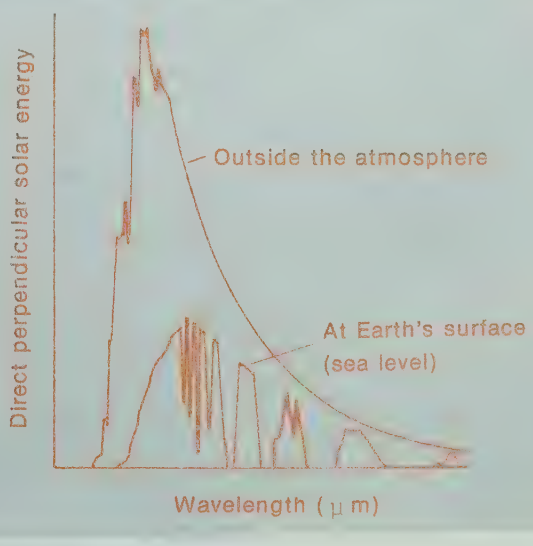


Sun Path Chart-49°N Latitude
Figure 8

The effect of absorption and reflection by the atmosphere is illustrated in the figures below. The amount of solar energy entering the atmosphere is shown for comparison. Note that both the outside of the atmosphere and the surface of the earth values were measured perpendicular to the incident direct radiation.



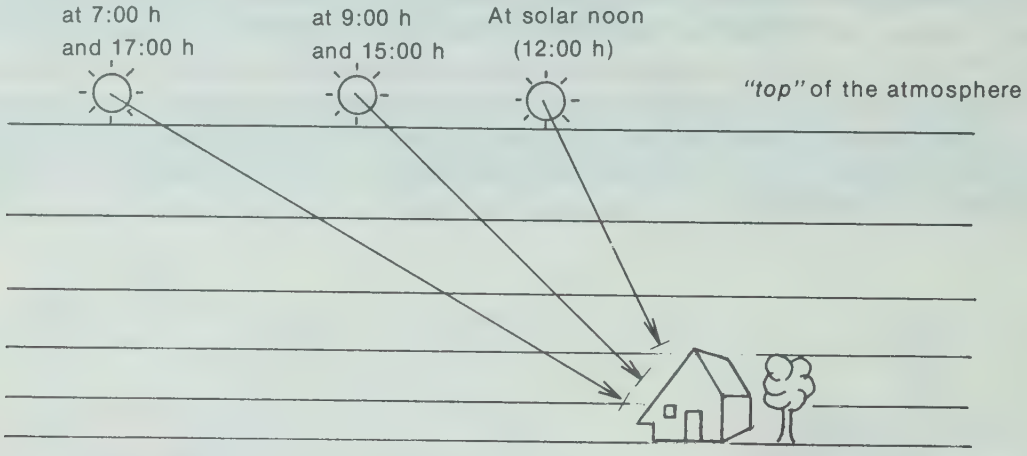
Atmospheric Absorption and Reflection
for Solar Altitude = 90°
Figure 9



Atmospheric Absorption Absorption and Reflection
for Solar Altitude = 11°
Figure 10

2a. Variation of Solar altitude and Pathlength During the Day

Solar altitude and azimuth vary with the time of day. The solar altitude determines the *pathlength* of solar radiation in the atmosphere as illustrated in Figure 11. The lower the solar altitude, the longer the pathlength and thus the greater the absorption and reflection of solar radiation.

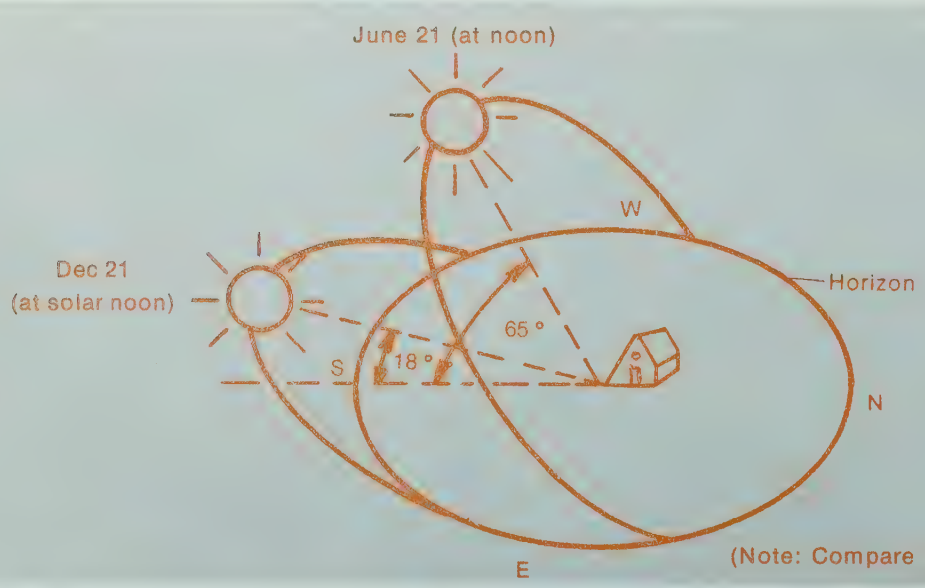


Variation of the Pathlength of Solar Radiation in the Atmosphere With Time of Day
Figure 11

(Note that the solar radiation is being measured perpendicular to the direction of the direct solar radiation.)

2b. Variation of Solar Altitude and Pathlength During the Year

There is also a seasonal change in pathlength of the solar radiation through Earth's atmosphere as shown in Figure12. Again, the lower the sun is on the horizon (i.e., the smaller the solar altitude), the longer the pathlength of the solar radiation in the atmosphere, and the greater the absorption of solar radiation by the atmosphere. The smaller the solar altitude, the less the solar radiation (as measured perpendicular to the direction of the direct solar radiation). Due to the 47° (23.5+23.5° in Figure 13) change in the tilt of Earth's axis relative to the solar radiation, the solar altitude from summer to winter will change by 47° (65° - 18° in Figure 12) at all latitudes.



(Note: Compare Figure 12 with Figure 8.)

Variation of the Pathlength of Solar Radiation in the Atmosphere with Time of the Year (Latitude 49° North)
Figure 12

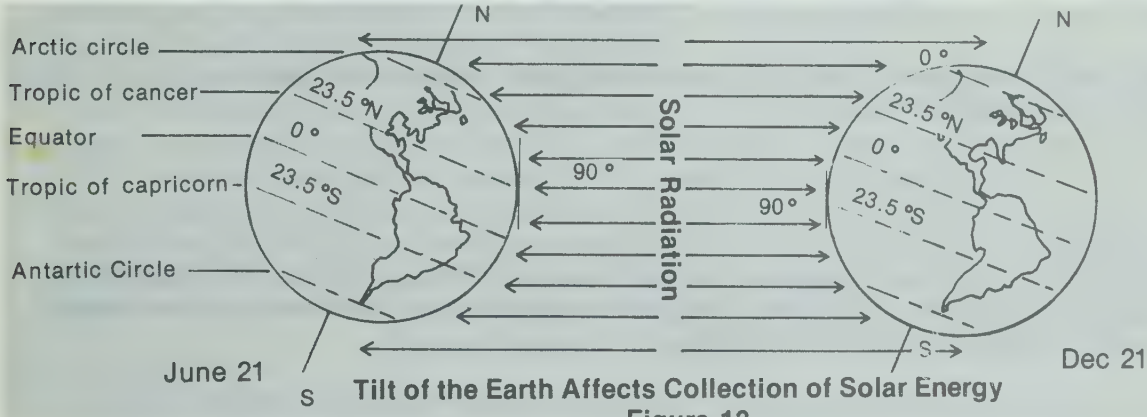
3. Variation of Solar Radiation Due to Tilt of the Collector (Earth)

Earth's surface is another boundary to the solar radiation. At Earth's surface, absorption and reflection are two process occurring with absorption being the larger factor. (See Figure 6.)

Reflection primarily from snow and water, results in a variable energy loss of the incident radiation. The reflected radiation may undergo absorption in the air, further reflection in the atmosphere, or continue out of the atmosphere into space.

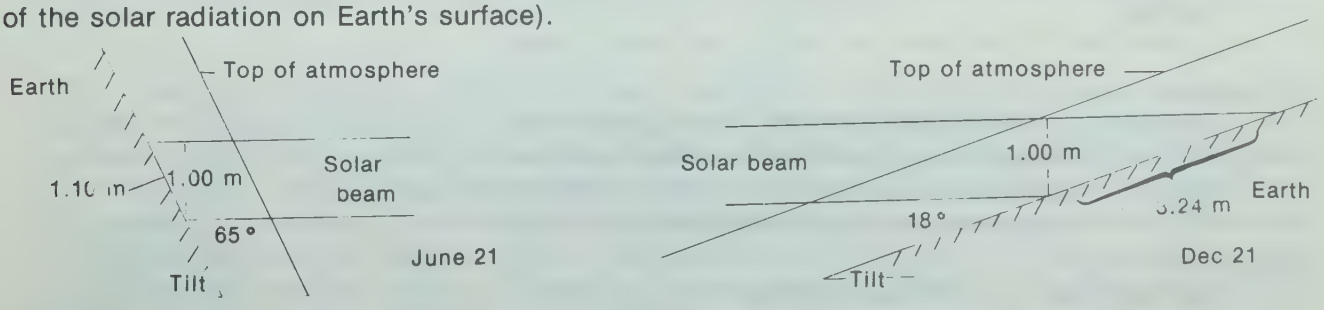
Absorption of solar radiation results in the heating of the absorber. The absorbing material (Earth) may dissipate the heat by conduction (land), convection (water), or radiation (land and water). In the latter case, the radiation emitted is in the IR region (heat radiation) and is of a longer wavelength (lower energy) than the incident solar radiation. These processes, absorption and radiation at a longer wavelength, are the basis of the *greenhouse effect* discussed later in the unit.

To this point the solar radiation has been discussed as if the solar radiation strikes a surface perpendicular to it (i.e., the tilt variable has been controlled (kept the same)). However, solar radiation striking Earth's surface is by definition striking a *horizontal* surface. Due to the tilt of Earth's axis, the tilt of a particular horizontal plane on Earth's surface varies with the time of the year (i.e., varies with the position of Earth in its orbit around the sun). From summer to winter the tilt of Earth's surface relative to the solar radiation changes by 47° (23.5° + 23.5°). (See Figure 13.)



Tilt of the Earth Affects Collection of Solar Energy
Figure 13

At northern latitudes the sun has its highest annual altitude at noon on June 21. At the Tropic of Cancer (23.5° north latitude) the sun will be directly overhead at noon (solar altitude, 90°). For points north of the Tropic of Cancer the solar altitude will be less than 90° at noon on June 21. For example, at latitude 49°N the solar altitude will be 65° at noon. On December 21 at northern latitudes the sun will have the smallest solar altitude. Since the intensity of solar radiation per unit horizontal area depends upon the solar altitude, the season will have a great effect on the amount of solar energy collected by Earth's surface in a given region. The seasonal effect is due to both the increased path length of the solar radiation through the atmosphere (resulting in an increased in the absorption and reflection of solar radiation by the atmosphere) and to the increased effective surface area which a perpendicular cross-section of radiation strikes (resulting in a decrease in the intensity of the solar radiation on Earth's surface).



The Change in Effective Surface Area with the Seasons
(Latitude 49°N)
Figure 14

Exercise:

1. What three factors affect the intensity of the solar radiation striking a horizontal surface on Earth? How do these factors affect the solar radiation intensity?

2. There may be a danger that the increasing use of fossil fuels will increase the carbon dioxide and soot concentration in the atmosphere. What effect will this increase in carbon dioxide have on the climate? What effect will the increase in soot have on the climate?

3. Absorption of some radiation by the atmosphere is very beneficial. Explain this statement with reference to the ozone layer. (The complete answer is not in this book.)

4. What variables affect the solar altitude?

5. Determine the tilt of the Earth relative to the solar radiation at 49°N latitude for June 21 and December 21 by reference to Figure 14.

6. If the solar altitudes at solar noon on June 21 at 53°N and at 40° N are 60° and 73°, respectively, what are the solar altitudes on December 21 at the same latitudes. What are the tilt of Earth's horizontal surface relative to the solar radiation in these situations?

In the table below match the terms with the explanation which defines the term. Also match the terms with the situation which the term best describes.

Term	Explanation (letter designation)	Situation (letter designation)
7. Conduction		
8. Convection		
9. Radiation		

Explanations

a. All substances above absolute zero emit IR radiation.
b. Hot fluids rise allowing cooler fluids to take their place.
c. Molecular energy is transferred from faster moving molecules to slower moving molecules by molecular collisions.

Situations

d. Heat escapes from a house in winter through walls.
e. A clear night is ofter colder than a cloudy night.
f. The air is generally warmer at the ceiling than at the floor.

Purpose:

To measure the relative intensity of solar radiation using a vane-type radiometer.

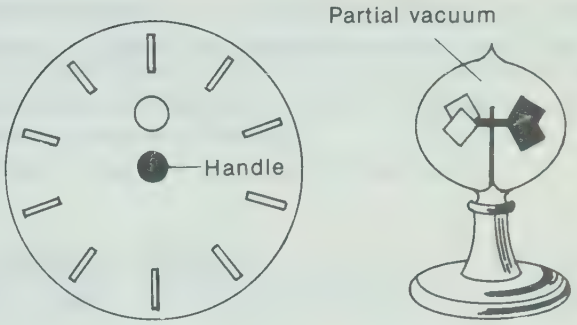
Materials:

1 or 2 - radiometers
8 or 16 - student stroboscopes
8 or 16 - stopwatches
1 - black plastic or paper (piece)
1 - large beaker (to cover radiometer)

Prelab Information:

1. Radiometer

A vane-type radiometer or simply radiometer, consists of four vanes at right angles to each other (see Figure 15). One side of each vane is white, the other side is black. The pivot has very little friction. Air resistance is minimized by the partial vacuum inside the glass envelope. Radiation striking the vanes is absorbed to a greater extent on the black side than on the white side. As a result the black side is at a slightly higher temperature and the gas molecules colliding with this side will gain more kinetic energy. The gas molecules exert a larger net force against the black side when they rebound from the hotter black surface. The gas molecules gain energy and rebound faster from the hotter black side and thereby impart a greater momentum to the black side. The net effect is a larger push on the black side of the radiometer vanes. The speed of rotation of the vanes tends to increase with the intensity of the incident radiation.



Stroboscope and Vane-Type Radiometer
Figure 15

2. Stroboscope

A simple stroboscope (see Figure 15) consists of a circular disc with a number of slits at equal intervals around the circumference of the disc. The stroboscope can be used to measure the time for one rotation of an object that is turning too fast for this time to be measured directly. If the disc has ten equally spaced viewing slits then the viewer gets ten glimpses of a rotating object for each rotation of the disc. When the frequency of glimpses through the stroboscope matches the frequency of the rotating object, the object will *appear to stand still* even though it is actually rotating.

When using a stroboscope with a spinning, 4-vane radiometer, the radiometer action can be stopped after, for example, two complete rotations, one complete rotation, one-half rotation or one-quarter rotation. To be sure which situation is being observed, always use the highest speed of the stroboscope which stops the motion. The highest stop-speed of the stroboscope stops the motion after every one-quarter turn of the radiometer.

As an example, consider a spinning, 4-vane radiometer which appears stopped (using the fastest stroboscope stop-speed) when 10 rotations of a 10-slit stroboscope take 5.0 s. The average time for one rotation of the *stroboscope* is 5.0 s divided by 10 rotations and equals 0.50 s/rotation. The average time for *one-quarter rotation* of the *radiometer* is 0.50 s divided by 10 slits equals 0.050 s. The average time (period) for *one complete rotation* of the *radiometer* is 0.050 s multiplied by 4 equals 0.20 s. The *frequency* of the rotation of the radiometer is the reciprocal of the period (e.g., 1/0.20 s) or 5.0 Hz (cycles per second). The frequency of the radiometer is a measure of the intensity of the solar radiation.

3. Definition of Weather Conditions

Describe weather conditions by the words - *clear, partially cloudy* or *overcast.* To describe the degree of overcast use the words - *distinct shadows, faint shadows* or *no shadows* - depending on how the shadow appears.

Prelab Exercise:

Refer to the Prelab Information and to the Observations and Calculations sections.

1. Why does the radiometer turn toward the white sides of the vanes? (A diagram may help.)

A rotating, 4-vane radiometer is observed with a five-slit, hand held stroboscope. Use this information to answer the next two questions.

2. If the stroboscope takes 8.2 s to make 10 turns to *stop* the radiometers movement, how long does the radiometer take to make one complete rotation? (The fastest stop-speed of the stroboscope was used.)

3. Calculate the frequency of rotation of the radiometer.

4. The radiometer vanes are acting as solar collectors. What is the tilt angle of these small collectors? Should the collectors be described as horizontal, perpendicular to the solar radiation or vertical? What is the effective solar collecting surface area expressed in terms of unit vane areas (i.e., 1, 2, 3 or 4)?

EARTH AS A SOLAR COLLECTOR
MEASURING SOLAR RADIATION—LAB 1

Procedure:

1. Place the radiometer on a horizontal surface well away from reflections or shade from buildings, trees, etc.
2. Record the time of day and date in the observations table.
3. Select and record the number of slits to be used on the stroboscope. (Generally the maximum number should be used.)
4. Obtain the fastest speed of the stroboscope which *stops* the motion of the radiometer vanes.
5. Time and record 10 rotations of the stroboscope while maintaining the *stopped motion*.
6. Repeat Step 5 twice more and average the three values.
7. Record the weather conditions (clear, partly cloudy, overcast, etc.) as defined in the Prelab Information.
8. Repeat Steps 1 to 7, as many times as possible, at different times of the day, on different dates, and/or with a large beaker inverted over the radiometer. (Use a black plastic or paper sheet under the radiometer and beaker to avoid condensation inside the beaker.)
9. (Optional) Determine and record the solar altitude and azimuth for each reading.

Observations:

	Time of Day	Date	Number of Slits (n)	Time for 10 Rotations of Strobe (s)				Beaker (yes/no)	Weather Conditions
				Trial 1	Trial 2	Trial 3	Ave.(T_{10})		
1									
2									
3									
4									
5									

Calculations:

	Average Time for One Rotation of the Strobe (s) $\left(T_s = \frac{T_{10}}{10}\right)$	Number of Slits (n)	Average Time for One Rotation of the Radiometer Vanes (s) $\left(T_r = \frac{T_s}{n} \times 4\right)$	Frequency of Rotation of Vanes (Hz) $\left(f_r = \frac{1}{T_r}\right)$
1				
2				
3				
4				
5				

Exercise:

1. Does the radiometer respond to direct, diffuse and/or reflected solar radiation? Answer in terms of the results of this lab.

2. Why is there a lower limit on the amount of incident radiation to which the radiometer will respond?

3. Why was a black rather than a white sheet used under the radiometer when the beaker was put over the radiometer?

4. What disadvantages does the radiometer have as a device for studying or measuring the solar radiation intensity?

Predict and explain the effect of the following factors on the frequency of rotation of the radiometer vanes. Keep all other variables constant except for the one being manipulated. If a prediction is not possible explain why. Note that the radiometer vanes are vertical not horizontal or perpendicular-to-the-radiation surfaces as have been considered in the previous part of this unit.

5. Time of day.

6. Time of year.

7. Clear summer day versus clear winter day.

8. With or without glass cover (beaker).

9. With a white paper (rather than black) under the radiometer and beaker.

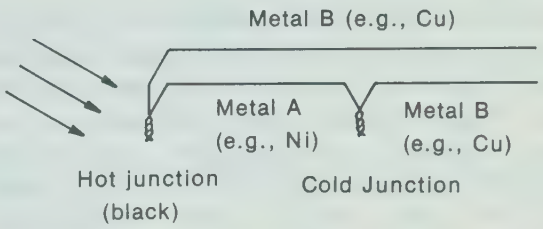
10. With white paper or aluminum foil on the inside back of the beaker.

Types of Radiometers

A moving-vane radiometer (*radiation meter*) was employed in the previous lab to determine the relative amount of solar radiation during a day. The moving-vane radiometer reacts to *direct* solar radiation by the relative *heating effect* on the two sides of the vanes. Other types of radiometers react to *direct, diffuse* and/or *reflected* solar radiation by a heating effect on a thermopile to produce electricity or by a photon effect on a solar cell to produce electricity.

Thermoelectric (Thermopile) Radiometers

A *thermopile* is composed of a series of thermocouples (thermopairs). A thermocouple is made by joining two dissimilar metal wires together at two points. When one thermo*junction* (the joined part) is heated, a thermoelectric current is produced.



A Thermocouple
Figure 16

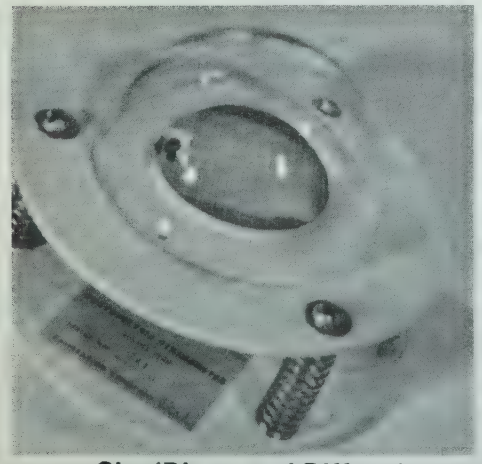
If the solar radiation is allowed to strike alternative black junctions, then the difference in temperature produces a thermoelectric current. The voltage produced is proportional to the temperature difference and thus to the intensity of the solar radiation. The thermopile (e.g., 10-120 junctions) is very sensitive to variations in solar radiation.

Photovoltaic (Solar Cell) Radiometers

Photovoltaic radiometers are less commonly used for measuring solar radiation than are thermoelectric radiometers. (The photovoltaic radiometer is more difficult to calibrate.) This type of radiometer employs a solar cell which converts solar energy directly into electrical energy (without an in-between heat energy stage). The operation of solar cells is described in Appendix 2.

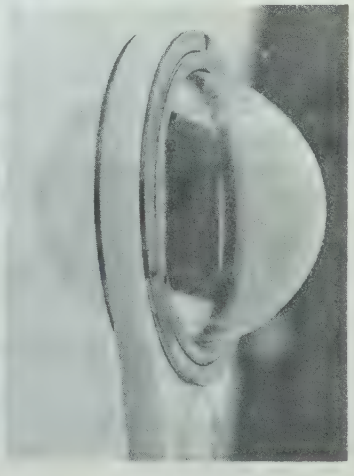
Direct, Diffuse, Reflected and Net Solar-Radiation Radiometers

The radiometers described above can be oriented and employed in a frame such that direct, diffuse, reflected and/or net solar radiation is measured. Some of these applications are pictured below.



Sky (Direct and Diffuse) and/or Reflective Radiometer
Figure 17

Diffuse Radiometer
(note shadow ring)
Figure 18



Net (Sky-Terrestrial) Radiometer

Figure 19

Measurement of Solar Radiation

The actual amount of annual solar radiation received by a horizontal surface at different locations on Earth depends primarily on latitude and cloud cover. At a particular location, the time of day and time of year result in variations in the intensity of solar radiation on a horizontal collector. (Factors such as the tilt of a solar collector will be discussed later.) Whereas some factors are predictable (latitude, time of day and year); the degree of cloudiness is difficult to predict. Over a long period of time the average amount of solar energy reaching Earth's surface at a particular location can be measured and the data used in the practical application of solar energy.

Mean Daily Solar Radiation on a Horizontal Surface for the Year

The mean daily solar radiation reaching a horizontal surface in North America over a year is shown in Figure 20. The source of the radiation data is based primarily on the observation network operated by atmospheric environment services in Canada and the U.S.A. The data takes cloud cover into account. For a particular location the average radiation can be estimated using Figure 20. The data sheet provided in this unit lists the mean daily solar radiation on a horizontal surface for each month of the year. The isohels (lines of equal solar radiation) on the map illustrate the effect of cloud (and other atmospheric contaminants) on the amount of solar radiation reaching a horizontal

Mean Daily Solar Radiation (MJ/(m^2·d)) for the Year on a Horizontal Surface
Figure 20

Exercise:
Estimate, using Figure 20, the mean daily solar radiation for your location. Use this estimate in answering the following questions.

1. How much energy would fall each year on a horizontal surface with an area of 100 m^2 (area of average home roof) at your location?
2. North Americans, on the average, use space heat at the rate of approximately 100 GJ/home/a. Compare this value with the answer to Question 1, and express the comparison as a ratio.

In a small North American city, about 500 000 people live in an area of approximately 300 km^2. Use this information plus information given in previous questions to answer the following three questions.

3. How much energy (in GJ) would these 500 000 people use in a year?
4. Calculate the amount of solar energy (in GJ) falling on the 300 km^2 area.
5. What percent of the solar energy is required to meet total energy needs?
6. Without cloud cover and atmospheric contaminants where would the isohels appear on the map in Figure 20?

Mean Daily Solar Radiation for Each Month

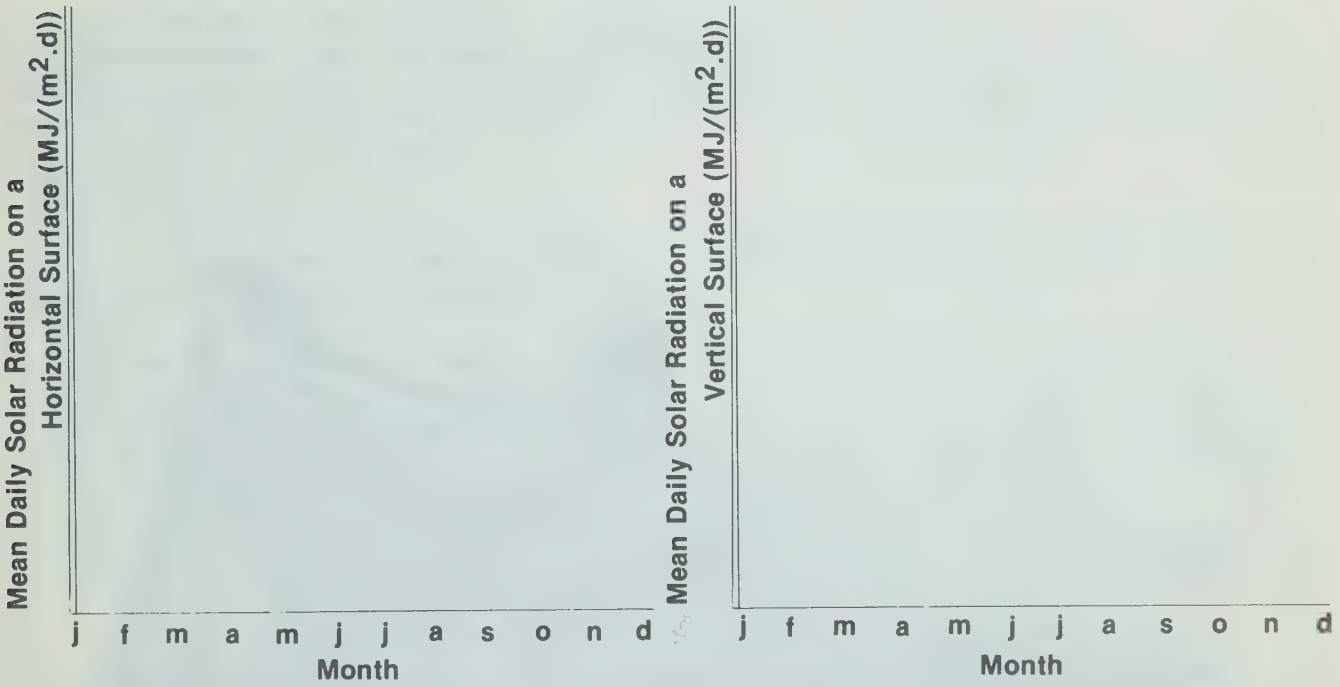
The amount of solar radiation striking a horizontal or vertical surface varies considerably from month to month during the year. Side 2 of the data sheet provides the actual mean daily solar radiation values for the months of the year for some major cities in Canada and the United States.

Transfer the solar radiation data for the city nearest your home from Side 2 of the data sheet to the table below.

Exercise:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Horizontal												
Vertical												

1. Sketch graphs of the mean daily solar radiation versus the month of the year for the horizontal and vertical data in the above table.


Mean Daily Solar Radiation on a Horizontal Surface (MJ/(m2.d))
j f m a m j j a s o n d
Month
Mean Daily Solar Radiation on a Vertical Surface (MJ/(m2.d))
j f m a m j j a s o n d
Month

2. Explain the monthly variation of mean daily solar radiation on a horizontal surface.

3. Explain the monthly variation of mean daily solar radiation on a vertical surface.

4. In what applications are horizontal solar data important?

5. In what applications are vertical solar data important?

Collecting Solar Energy

In the previous section the above principles were applied to Earth as a collector of solar energy. In this section the above principle will be discussed in the context of the dwelling as a solar collector (i.e., a passive system). Later in the unit the above principles will be discussed in the context of a specialty apparatus as a solar collector (i.e., an active system). The same basic principles apply to all three collectors. (It should be noted that Earth as a solar collector is mainly a horizontal surface while dwellings and special collectors usually use either vertical or tilted surfaces.)

Active and passive systems differ primarily in how the solar energy collected is transferred. In active systems heat transfer occurs by mechanical means; whereas in passive systems heat transfer occurs by natural means (i.e., radiation convection and conduction). Active and passive systems are often portrayed as competing systems. Both have their place in a solar society. Unfortunately the high technology active systems have been promoted by government and industry as the only solar solution to our energy problems. (For example, many government tax credits are available for active but not for passive systems.) This position ignores the fact that passive space heating systems are less expensive and more reliable than active systems.

Passive Design Solar Collectors

Passive designs for solar energy collection are systems which do not use active components (e.g., pumps, fans, pipes and complex heat storage units). *Passive* systems are more natural, less sophisticated, less mechanical and less costly than active systems. Most systems can be easily classified as passive or active although some systems are hybrids (i.e., a mixture of passive and active).

The main attractions of passive designs for solar energy collection are their simplicity and familiarity. Knowingly or unknowingly most owners or renters of dwellings benefit from solar heat energy collected during daylight hours when the outside temperature is lower than the inside temperature. Ironically, the passive collection of solar energy is given more attention when the heat energy is unwanted - on hot sunny days when dwellings become too warm.

All dwellings on Earth that have windows are passive solar collectors. Each dwelling can have its energy efficiency maximized by:

1. controlling the entry of solar energy
2. minimizing the loss of the energy collected
3. increasing the collection and storage capacity

These variables must be balanced one against the other in order to attain optimum efficiency (i.e., extra windows allow more energy to enter but may require extra storage capacity to prevent overheating and will result in more energy loss). Besides the collection variables, consideration must be given to structural strength, aesthetic design, location, capital cost, amortized cost and cost of competing energy sources.

1. Controlling Entry of Solar Energy

The passive collection of solar energy may be optimized by combining the following aspects in the most energy and cost efficient manner possible.

a. The effective area of windows facing the sun during daylight hours should be optimized. Increasing the south facing windows will increase the amount of solar energy which enters a dwelling. The area of south facing glass should be one-tenth to one-third of the floor area of the dwelling. The effective area of glass may be increased by making the glass area perpendicular to the sun at noon on winter days. East or southeast facing windows are generally given preference over west facing windows because the heat demand in the morning is greater than in the later afternoon or evening, and because of heat loss through west windows due to cold west winds. North facing windows are not energy efficient (i.e., north windows result in a net energy loss).

b. The amount of solar energy collected passively (or actively) by a dwelling will be affected by trees and buildings which block the sunlight. Evergreen trees should not be planted where they block the sun. Deciduous trees planted to the south of the dwelling will block the unwanted sunlight in the summer but will allow the sun through in the winter. The legal right to sunlight is now being advocated by solar energy groups to protect passive and active systems from tall buildings being built adjacent to solar dwellings. Urban planning is also required in order to run all streets east and west so that adjacent buildings do not shade the southside of a dwelling.

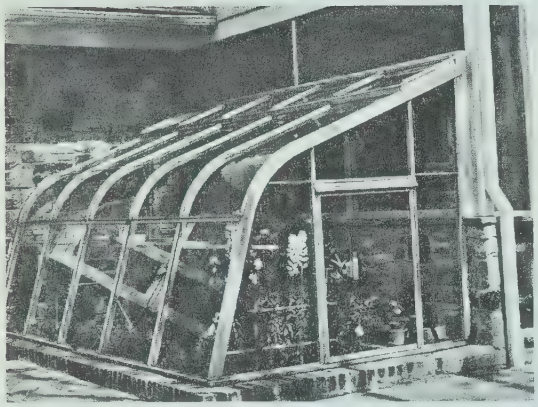
c. Vertical structural projections on the outside of a house can restrict, or in some cases, increase the entry of solar energy depending upon the requirement (e.g., jogs on the south wall or protruding windows on the east or west wall).

d. Shading devices such as roof overhang, trellises, shutters and curtains control entry of solar energy to prevent overheating during the summer months.

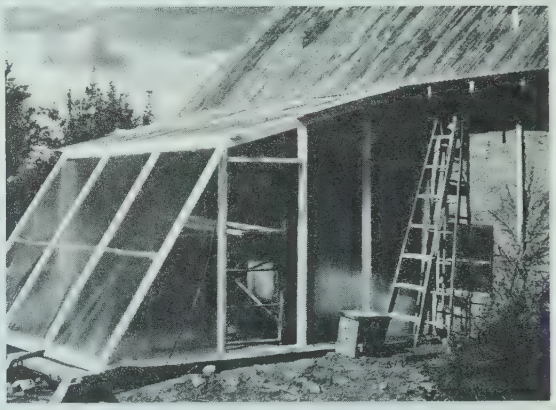
Example 1: Solar Greenhouses

A solar greenhouse may be added-on (retrofitted) or built-in to a house or apartment building. The solar greenhouse usually has several purposes. The large amounts of glass or plastic allow entrance of large quantities of light and heat energy. The light is used for growing decorative and edible plants year-round and for providing light to the dwelling for human activities. The heat collected may be used immediately or stored for future use. Attached solar greenhouses can collect and store solar energy much more conveniently and aesthetically than can standard living rooms.

The built-in greenhouse system may be one of the things that makes solar energy really take hold in the commercial house market. Some of the most beautiful houses built are those which incorporate greenhouse areas as part of the living space. The fact that energy savings up to 50% might be accrued at the same time almost seems like a bonus.



Commercial Retrofit Greenhouse
Figure 21



Homemade Retrofit Greenhouse
Figure 22

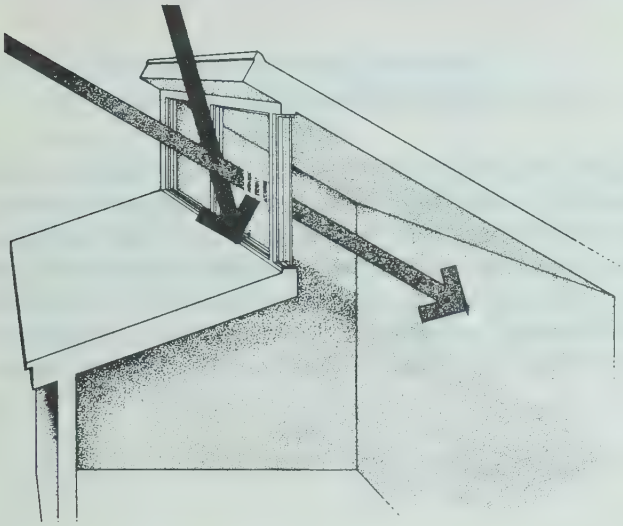
Integrated Greenhouse—Exterior
Figure 23a

Integrated Greenhouse—Interior
Figure 23b

Example 2: Clerestory Windows

South-facing clerestory windows help to solve the problem of getting solar heat and light into the north part of an open beam dwelling. The clerestory windows have traditionally been used as skylights to provide light and an aesthetically pleasing architecture. However, they are very practical, energy efficient solar energy (heat and light) devices as well as being attractive. To prevent glare and to increase storage and prevent overheating glass which produces diffuse light may be used in clerestory windows. Sometimes multiple tiers of clerestory windows are used for providing heat and light to various places in a dwelling. Clerestory windows can also be useful for venting hot rising air from a dwelling on hot summer days. Shutters could reduce overheating in the summer and, if insulated, reduce heat loss in the winter.

Unlike greenhouses which may be retrofitted to a house, clerestory windows are usually part of the original design of the house. Most passive solar applications are dependent on design features rather than on the addition of mechanical devices. This emphasizes the need for the education of or public pressure on architects, builders and urban planners.



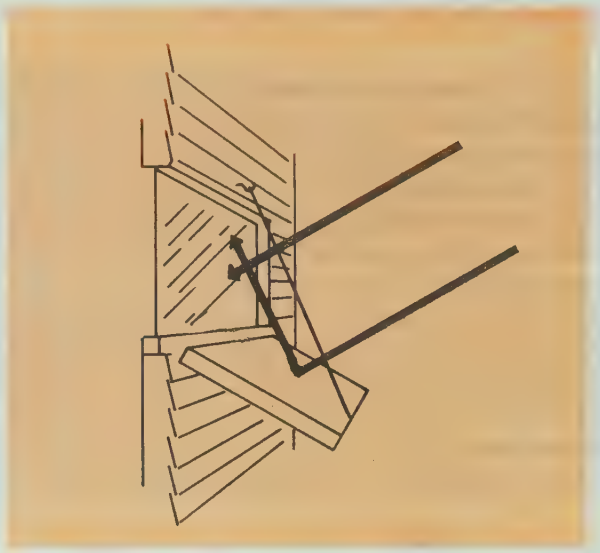
Principle of Clerestory Windows
Figure 24

Clerestory Windows
Conventional Residential House
Figure 25

Clerestory Windows
Unconventional Design
(Note: House is set into the side of a hill for added insulation and weather protection.)
Figure 26

Example 3: Reflectors and Shutters

The effective window area of a dwelling may be increased by use of fixed or movable reflectors. For vertical glazing the reflector length should be one to two times the height of the glazed opening. For south-sloping skylights the reflector should be approximately the same size as the skylight. The reflector angle can be fixed for the heating season. By using reflectors, the average winter solar radiation incident on a window or skylight can be increased by up to 60%. When possible, reflectors should be designed to function as insulating shutters and/or shading devices.

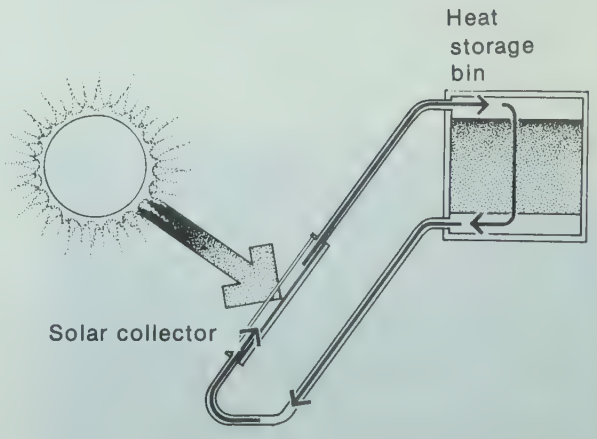


Reflecting and Insulating Shutter
(May also be mounted vertically.)
Figure 27

Example 4: Passive Collectors

In the previous examples the emphasis have been on *directly* increasing entry of solar energy into a dwelling where it is then converted by absorption into heat. Passive collectors *indirectly* increase entry of solar energy by first converting the solar energy into heat energy on a dark surface. The air above the surface gains heat by conduction, becomes less dense and then rises out of the collector. This allows cooler air (from the house) to be drawn into the collector. This natural movement of a fluid, such as air, is known as a *convection current* or *thermosiphon*. In general, passive collectors should be kept low relative to the dwelling in order to utilize the thermosiphon effect.

Retrofit Passive Air Collector
Figure 28



Convective Loop Passive Collector
Figure 29

PASSIVE COLLECTION OF SOLAR ENERGY
THERMOSIPHON—LAB 2

Purpose:

1. To observe a thermosiphon or convection current in a fluid.

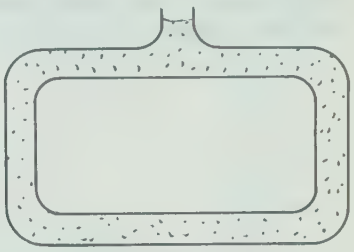
2. To relate thermosiphons to the passive collection of solar energy.

Prelab Exercise:

Explain, in terms of the kinetic molecular theory, the effect of heat energy on a fluid.

Materials:

1 - glass convection loop
1 - heat source (bunsen furner, alcohol lamp or candle)
1 - dropping bottle of concentrated food coloring



Convection Loop
Figure 30

Procedure:

1. Following a correct procedure, light the heat source. (If using a bunsen burner obtain and use a small, blue flame.)
2. Fill the convection loop with tap water to about the mid-point of the entry tube.
3. Holding the convection loop in one hand, gently heat the bottom opposite corner of the loop.
4. After approximately one-half minute add 1 drop of food coloring.
5. Continue heating for several minutes and observe the food coloring.
6. Record observations directly on Figure 30.
7. Empty and rinse the convection loop.

Questions:

1. Explain the movement of the water as shown by the food coloring.

2. For a two storey home, explain the best location of a passive water collector and hot water storage tank.

Briefly explain the importance of a thermosiphon in each of the following:

3. space heating a dwelling with an attached greenhouse

4. summer cooling in a clerestory dwelling

5. insulating shutters or curtains

PASSIVE COLLECTION OF SOLAR ENERGY
CONTROLLING ENTRY OF SOLAR ENERGY

Exercise:

1. In terms of solar azimuth explain why windows on the south side of a dwelling are the best solar collectors.

2. Why is the mean daily solar radiation incident on a vertical south-facing surface less in June than in February? (Refer to the data sheet.)

3. List the factors to be considered when comparing the collection of solar energy in Toronto, Edmonton and Vancouver or in Minneapolis, San Antonio and Los Angeles.

4. List examples of methods used to directly increase entry of solar energy and directly decrease entry of solar energy.

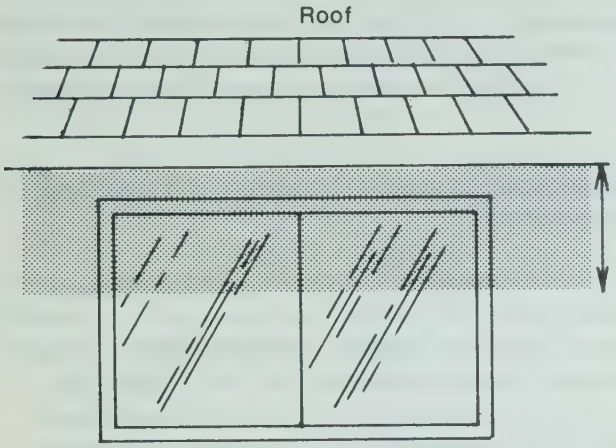
(increase entry)	(decrease entry)

5. Determine the ideal area-range of vertical south-facing windows recommended for a 110 m^2 dwelling and for your dwelling. Why is the area-range so widespread?

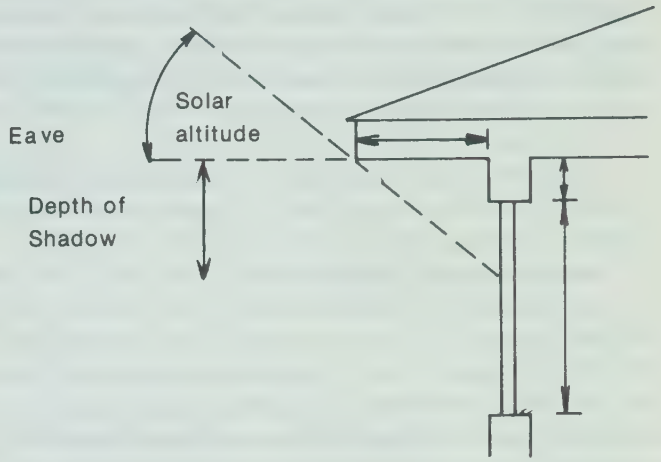
(110 m^2 dwelling)	(your dwelling)

6. Determine the actual gross area of south-facing windows in your dwelling and express this area as a percentage of the floor area.

7. Roof overhang is an important method used to *control* the entry of solar energy. The figures below illustrate the function of a roof overhang for a typical window-overhang situation.



Front View



Use the above diagram, the solar altitude for your closest latitude (see data sheet) and trigonometry to determine the depth of shadow for each of the dates given in the table below. Determine the net window area in direct sunlight at solar noon.

Time of the Year		June 21		May 21 July 21		Apr 21 Aug 21		Mar 21 Sept 21		Feb 21 Oct 21		Jan 21 Nov 21		Dec 21	
Solar Altitude (at solar noon)	Depth of Shadow (m)														
Net Window Area Area in Direct Sunlight at Noon(m^2)															

8. Calculate the amount of solar energy entering five 1.50 m by 0.75 m clerestory windows at your location during the month of January. How much would this energy be worth using local heating costs? (Assume 1.0 ¢/MJ if local costs are not available.)

   From data sheet obtain the:

   a. January mean daily solar radiation incident on a vertical south-facing surface for the location nearest you. _____

   b. glazing transmission coefficient for double glazed glass windows. _____

2. Minimizing the Loss of Solar Energy Collected

In the previous section factors affecting the increased entry of solar energy were discussed. A second set of factors, which increase the potential of using a dwelling as a passive collector, are those which minimize the loss of the solar energy collected. Minimizing the loss of the *solar* energy colected is not much different for a solar dwelling than for a regular dwelling except for the location and area of windows.

Energy losses may be minimized by (a) decreasing air infiltration through the dwelling, (b) increasing the insulation and c. decreasing the window area.

a. Decreasing Air Infiltration

The best return on money spent to save energy is money spent to decrease air infiltration. The majority of current dwellings have substantially more than one complete air exchange per hour. With a little construction care and a small investment of money, the number of air exchanges per hour on a new home can be decreased to 0.3-0.05/h. On new dwellings the major way to decrease air infiltration is to provide an integral, air-tight, vapor barrier. The vapor barrier is increased in thickness from 50 μm to 150 μm, is made continuous by caulking and stapling joints, is added around windows and is doubled and caulked around electrical outlets on outside walls. Care must be taken when finishing the inside of exterior walls that the vapor barrier is not cut. (The electrical outlet and cutting problems are eliminated by double wall construction techniques described on the next page.)

In both new and older homes, air infiltration may be decreased by weatherstripping doors and attic hatches, by caulking plumbing, furnace and fan stacks, by adding an entry air-lock, by using outside combustion air for fireplaces and furnaces, by decreasing wind effects by planting evergreen trees on the north and by employing electronic, rather than pilot-light ignition furnaces and hot water tanks. Older homes may be further improved in terms of air tightness by caulking behind electrical outlets and baseboards.

Increased air tightness does not produce the commonly thought problem of lack of fresh breathing-air but does produce an excess of humidity for winter conditions. The high humidity from cooking, bathing and breathing can produce large amounts of condensation on cold windows. A solution is an air-to-air heat exchanger. Hot humid air is exchanged over cold, outside, intake air separated by polyethylene or metal sheets. Seventy-five-percent-plus of the heat from the exchanged air is recovered by the heat exchanger.

b. Increasing Insulation

With dramatic increases in the cost of fossil fuels during the last decade, there has also been a dramatic increase in the amount of insulation that is cost effective. The recommended amount of insulation in cold climates has been increased from *RSI*1 and *RSI*2 to *RSI*6 and *RSI*10 in exterior walls and ceilings, respectively. Some experts are now arguing that even these values should be increased so new houses can meet standards one to three decades from now. (*RSI* is an international system of measuring thermal resistance. See the *RSI* units and *RSI*/cm values for various materials on the solar data sheet.)

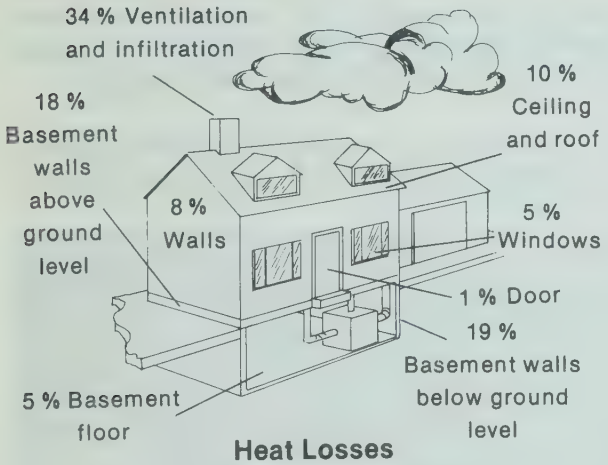
Additional means of increasing insulation are to add insulating shutters, insulating curtains, earth berms, double or triple glazing, insulation to the inside or outside of basement walls, and/or rigid styrofoam insulation or an extra wall with fibreglass insulation to the outside of existing above ground walls.

c. Decreasing the Window Area

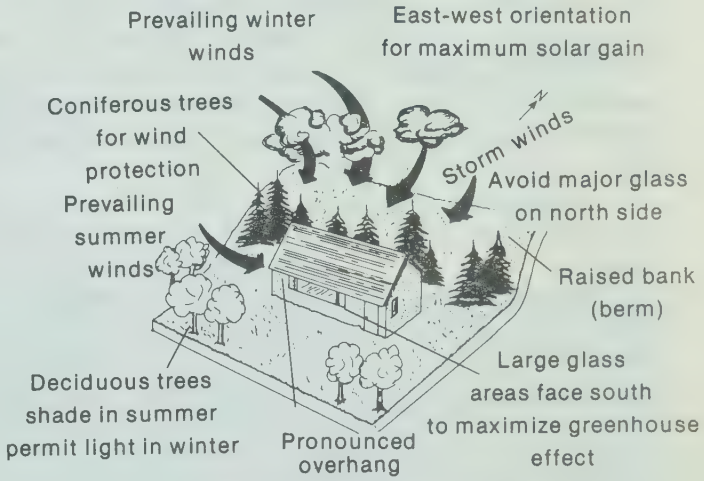
Double-glazed windows are typically *RSI*0.35 compared to walls of *RSI*1 to *RSI*6. The relatively large heat losses through windows are offset by solar heat gains if the windows are on the south or south-east. As the difference between the inside and outside temperatures increases and as the length of the winter night increases (i.e., as dwellings in the more northern latitudes are considered), the amount of *energy effecient*, south-facing glass decreases from 70% of the floor space in southern latitudes to 10% of the floor space in the north. (A typical modern home has a *total* window area equal to about 10% of the floor space.)

Currently the only ways to decrease heat losses through windows is by going to double and triple glazing or to insulating shutters or curtains for night use. The discovery of a transparent insulation that could be used for window glazing would be a big step forward for passive solar heating in more northern latitudes.

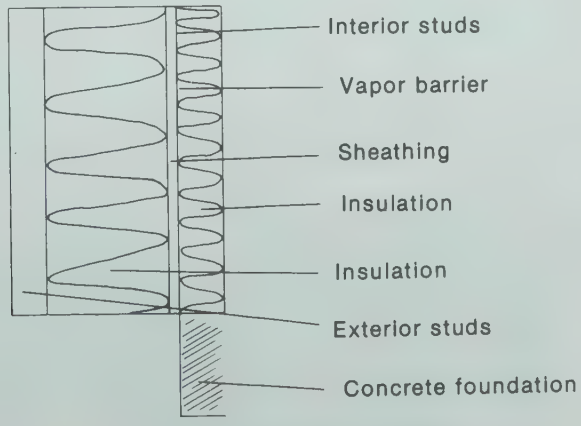
The implementation of the above factors for decreasing the loss of solar energy collected would qualify a home to be called a *low energy, passive solar heated home.* The combination of low energy and passive solar heating can reduce home energy consumption to about 10% of todays level.


34 % Ventilation and infiltration
10 % Ceiling and roof
18 % Basement walls above ground level
8 % Walls
5 % Windows
1 % Door
19 % Basement walls below ground level
5 % Basement floor

Heat Losses
Figure 31


Prevailing winter winds
East-west orientation for maximum solar gain
Coniferous trees for wind protection
Prevailing summer winds
Storm winds
Avoid major glass on north side
Raised bank (berm)
Deciduous trees shade in summer permit light in winter
Pronounced overhang
Large glass areas face south to maximize greenhouse effect

Orientation and Landscaping
Firgure 32



Double-Wall Construction
Figure 33

3. Increasing Passive Collection and Storage Capacity

Radiation passing through windows becomes trapped in the dwelling by the *greenhouse effect*. Most of the entering radiation is absorbed by the furniture, plants, decoration, walls, ceilings and floors in the dwelling. Because all objects emit IR radiation with a wavelength dependent upon the temperature of the object, IR radiation is re-emitted. The re-emitted IR radiation is at a lower energy and longer wavelength than the entering solar radiation. Window glass is not as transparent to the longer wavelength re-emitted IR radiation and as a result some of the IR radiation is trapped. In a dwelling filled with air, the air is also trapped by the glass. The glass therefore reduces heat loss from both radiation and convection (besides having insulation value). The total result is called the *greenhouse effect.*

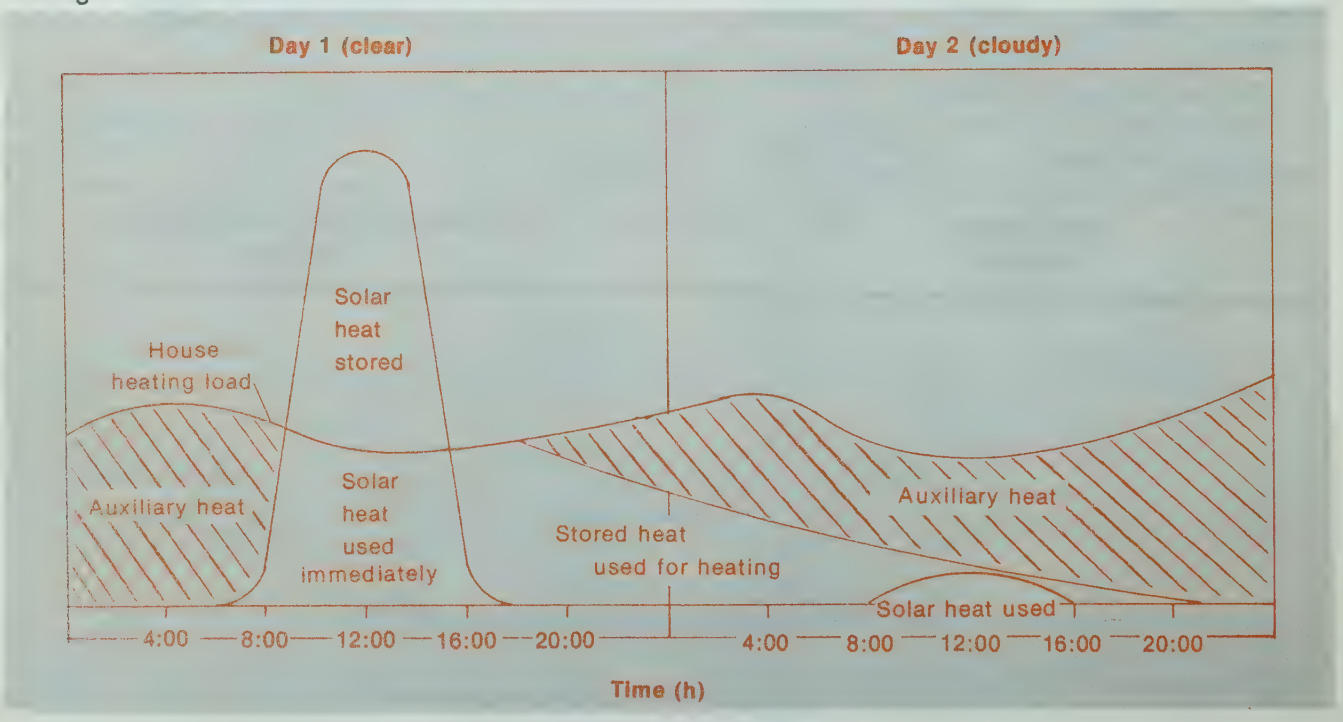
The amount of solar energy that can be absorbed without being immediately re-emitted will depend upon the thermal mass in the dwelling. The thermal mass is required to:

1. store some of the solar energy to prevent overheating of the dwelling during periods of maximum solar energy collection
2. store solar energy as heat for subsequent use during nights and cloudy periods

During nights and cloudy periods the thermal mass will radiate and conduct heat to the air, objects and people in the dwelling.

The thermal mass includes all mass in the dwelling. The mass in direct sunlight will absorb the most radiation. Other variables besides location, which affect the amount of solar energy stored as heat energy, are color, thermal conductivity, surface area, specific heat capacity, mass and temperature change. The thermal mass of a dwelling may be increased by manipulating these variables. A simple manipulation would be adding furniture or plants. Less common, but more effective, would be the addition of large containers of water or a thick concrete floor or wall.

Containers of hydrated (eutectic) salts in a home or greenhouse offer an alternative to thermal mass storage. Heat energy is stored as the result of a phase change rather than a temperature change.



Solar Collection and Heat Load
Figure 34

PASSIVE COLLECTION OF SOLAR ENERGY
COLOR OF SOLAR ABSORBERS—LAB 3

Purpose:

To compare effectiveness of different colors of solar radiation absorbers.

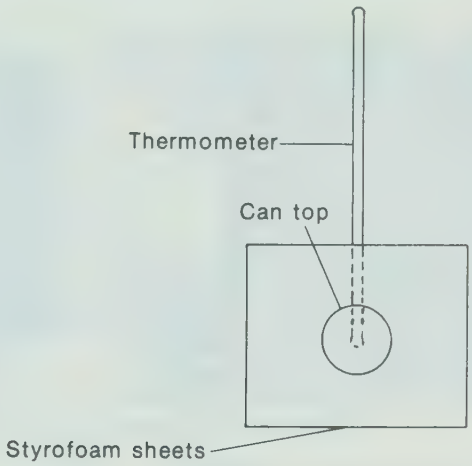
Prelab Exercise:

1. Predict the order, from best to worst, of effectiveness of the colors to be used in this experiment.

2. Will the temperature of a solar absorber continue to rise indefinitely as long as it receives solar radiation? Explain briefly.

Materials:

- paint (black plus other available colors)
1 - sheet styrofoam
3 - solar absorber panels prepared from tin cans (1-unpainted metal, 1-black and 1-green)
3 - thermometers (-10° to 110°C)
1 - 150 W floodlight (if experiment is done indoors)
1 - watch or clock



Solar Absorber Panel
Figure 35

Prelab Procedure:

1. Cut the ends out of 3-5 small tin cans. (Alternatively, about 5 cm of the sides could be left with the lids.)
2. Paint one side of each tin can lid a different color. (Alternatively, paint the insides of the shortened tin cans.)
3. Cut two 20 cm squares of styrofoam for each lid or short can.
4. Use a tin can to cut central holes in half of the styrofoam squares.
5. Glue the styrofoam squares together in pairs. (A square with a hole on top of a square without a hole.)
6. Glue a lid or short can into the bottom of each hole.
7. If the shortened cans are used, insulation or glazing may be added for comparison purposes.

Procedure:

1. Place thermometers carefully into the absorber panels and allow the apparatus to reach the ambient temperature.
2. Record date, ambient temperature in the shade, and relevant weather data (wind and cloud) in the observations section.
3. Set the three solar absorber panels normal (perpendicular) to the incident radiation (sunlight or lamp).
4. Record the initial time.
5. Record the temperatures at two minute intervals for 20 min.
6. Note any weather changes during the experiment.

Observations:

Date_____ Ambient temperature_____ Initial time_____ Weather conditions:_____

Time (min) / Color	0	2	4	6	8	10	12	14	16	18	20
Unpainted											
black											
green											

Exercise:

1. On the same graph, plot the temperature difference (thermometer reading minus ambient temperature) versus time for each colored surface.

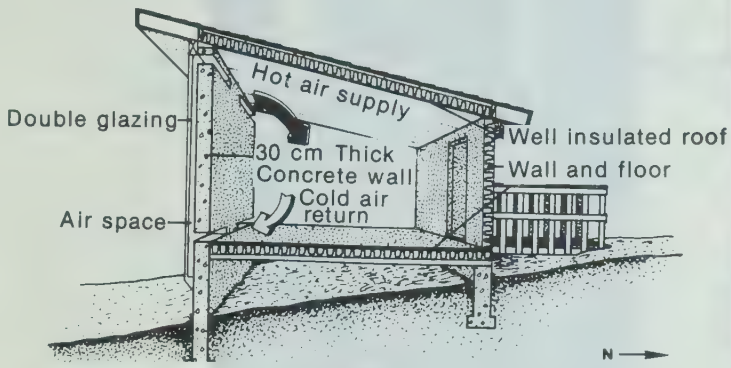
2. Rank the absorber surfaces from best to worst and compare with the prelab prediction.

3. What is the significance of the slopes of the graphs for the first ten minutes of observations?

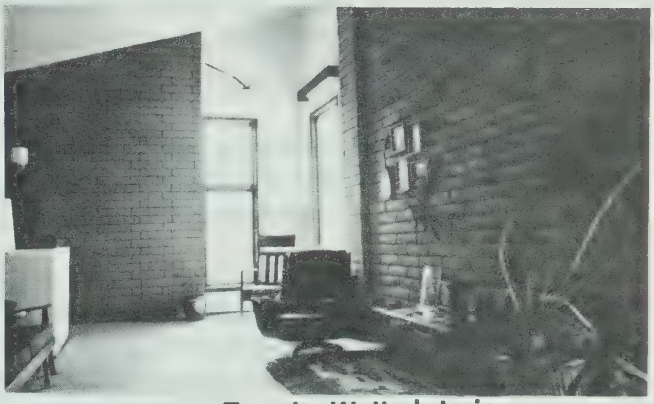
4. Explain, in terms of heat transfer, the plateau regions of the graphs.

Example 1: Trombe Wall

A Trombe wall (named after F. Trombe of France) is a device used for collection, storage and distribution of energy from the sun. A Trombe wall is a dark-colored concrete, stone or brick wall placed in the direct sunlight inside a south window. The Trombe wall generally has a large surface area, good thermal conductance, large heat capacity and a large mass. The Trombe wall maximizes all of the variables necessary to a large thermal mass. Besides collecting and storing solar energy the Trombe wall has the added advantage of producing convection air currents which help to circulate heat in the dwelling. The convection currents (a thermosiphon effect) continue as long as the Trombe wall is warmer than the air in the dwelling.



Trombe's House
Figure 36



Trombe Wall—Interior
Figure 37

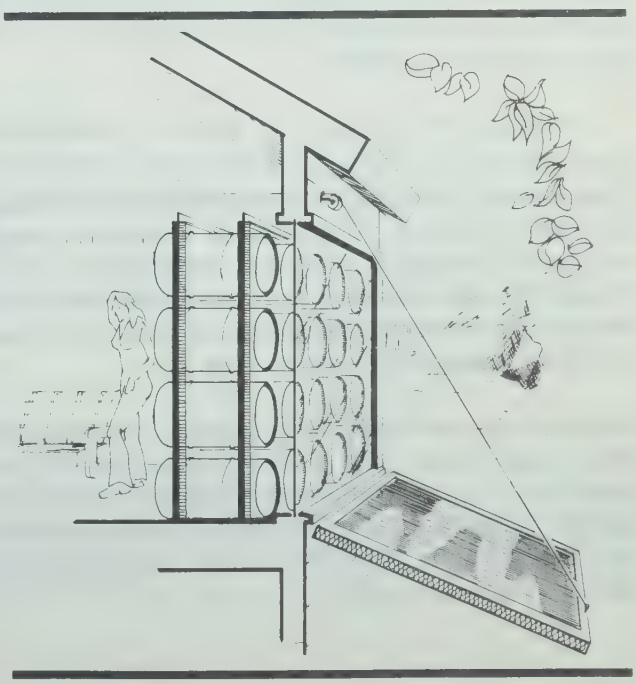
The cooler air is warmed by conduction (striking the Trombe wall) or by absorption of primary or secondary radiation as the air circulates by convection. A manually or thermostatically operated damper controls the flow of air. Ducting and a blower may be employed to move the warm air to other rooms in the dwelling. The interior of the Trombe wall could be a brick or stone feature-wall which acts as an IR radiator.

Example 2: Water Walls

Because water absorbs heat quickly and in large amounts relative to its volume, it is a very attractive thermal storage medium. A dark colored concrete or steel container of water may be placed directly inside a south-facing window or in the interior of a dwelling if skylights or clerestories are used. All passive water storage systems can reverse roles from heating in winter to cooling in summer.

A concrete or steel water wall may be contructed to look like an ordinary wall and often forms part of the structure of a dwelling. This type of wall takes up little space, has the least visual impact but involves more complex construction techniques compared to other types of water walls.

A drum wall consisting of large (approximately 200-250 L) water-filled drums supported in a rack is relatively simple to contruct, but has a large visual impact. The use of many individual containers, such as drums, minimizes the problem of temperature stratification within the water wall.



Drum Wall and Reflective Shutter
Figure 38

Culverts may be capped and set vertically in from a south window. They are filled with water, painted a dark color and act in the same fashion as drum walls. One advantage of the culverts is that they are generally considered to be more attractive than drum walls. One disadvantage is that the hot water thermosiphons to the top of the culvert and as a result the major heating effects will be near the ceiling.

Culvert Storage
Figure 39

Example 4: Massive Interior Floors or Walls

Floors or interior walls made of concrete or brick can not only add to the thermal mass in a dwelling but also act as passive solar collectors.

A dark concrete floor (possibly covered by attractive masonry tiles) allows the collection of solar energy without blocking the solar light or the view through the south windows. The floor will heat the objects in the room by radiation, conduction and convection. Having the heat come from the floor is very comfortable as long as the floor is sufficiently massive to prevent uncomfortable surface temperatures.

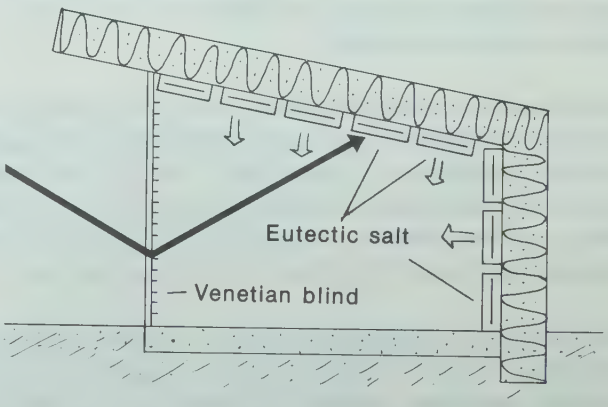
Example 5: Eutectic Salts

Eutectic salts are hydrated salts such as sodium sulphate decahydrate ($Na_2SO_4.10H_2O_{(s)}$, Glauber's salt). At about 32°C the Glauber's salt *melts*. Actually, the salt dehydrates and dissolves in its water of hydration.

$$Na_2SO_4 \cdot 10H_2O_{(s)} + \text{heat} \longrightarrow Na_2SO_{4(aq)} \quad (\text{at } 32°C)$$

The eutectic salt is an attractive solar storage medium because it stores a relatively large amount of heat at a fairly low temperature. The phase change absorbs much more heat than any reasonable temperature change of an equal mass of water, concrete, brick or rock.

Since the eutectic salt at its melting point would be too hot to be used in the floor, one solution has been to use reflective Venetian blinds to reflect the solar energy to ceiling tiles filled with a eutectic salt. (Eutectic salts are discussed again in later sections.)



Reflective Venetian Blinds and Eutectic Salt
Figure 40

Exercise:

1. List two functions of a thermal mass.

2. List the variables which affect the amount of solar energy which will be collected and stored by a thermal mass.

3. Compare heating effects of an open, masonary fireplace and of a thermal mass in terms of heat transfer to a room.

4. Explain how thermosiphons work.

5. List the main advantages and a disadvantage of Trombe walls.

6. Calculate the average maximum amount of solar energy that could be received per day in February by a 2.0 m by 4.0 m Trombe wall behind a double glazed window. Assume the Trombe wall is a south-facing, nonshaded, vertical wall at your location. (See solar energy data sheet)

7. List one advantage and one disadvantage each for drum walls, vertical culvert storage, concrete floors, interior brick walls and eutectic salts as means of collecting and storing solar energy.

8. Comment on the following statement. "Solar energy is a free, nonpolluting and renewable source of energy."

Introduction to Quantitative Aspects of Heat Storage

Collection and immediate use of solar energy can result in energy savings of up to 30%. Solar heat storage is important not only to prevent overheating, but also to further increase the energy savings up to 50% or more. In order to effectively utilize the different passive heat storage systems (e.g., Trombe wall and drum wall) discussed in the previous section, several calculations and decisions are required. The size and type of heat storage must be determined by the consideration of the amount of solar energy available, the heating demand of the house, the economics of the system and also the aesthetics of the final product.

This section will focus on the main types of passive heat storage and the basic calculations required to determine the quantity of heat stored in each type.

Materials used to store heat should ideally have the following characteristics:

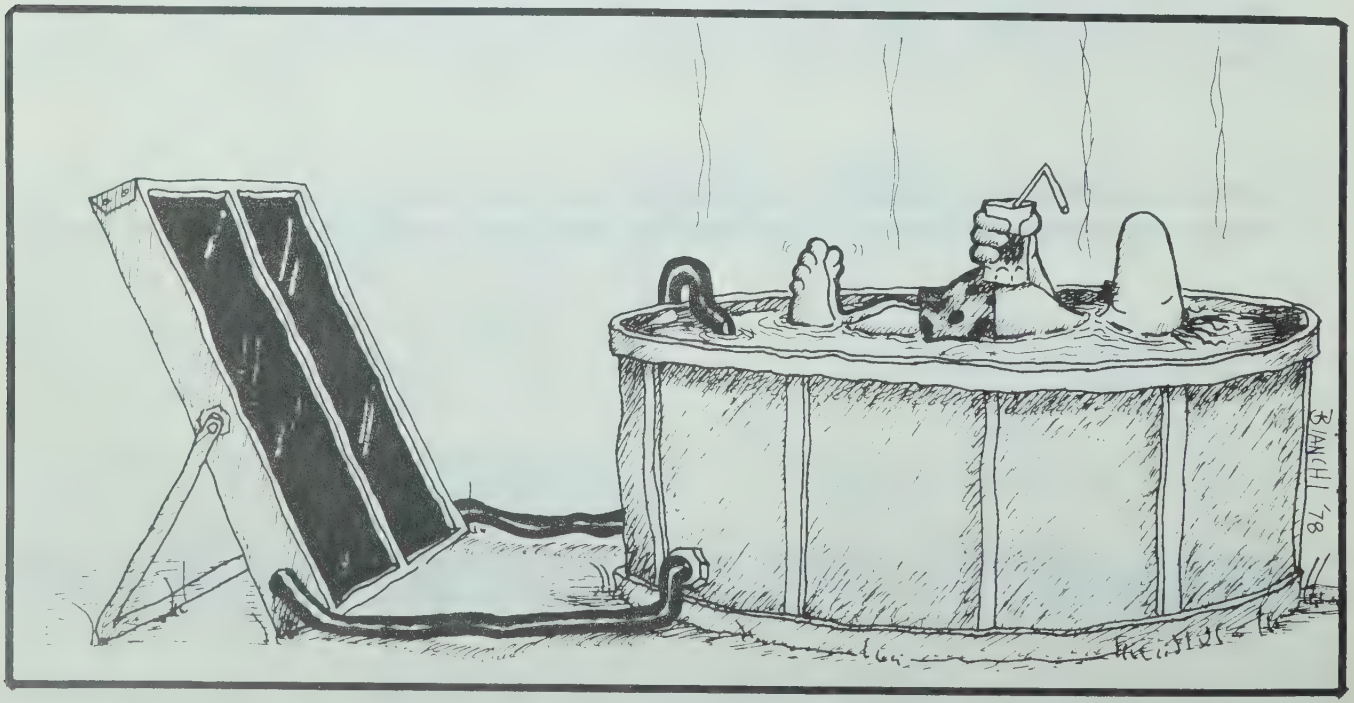
a. abundance and cheapness
b. high heat storage capacity per unit volume or per unit mass
c. ability to conduct heat readily

Two types of heat may be stored in a heat storage system.

1. *Thermal heat* is the heat stored as a result of a temperature rise in materials such as water, rock or concrete.

2. *Latent heat of fusion of eutectic salts* is the heat stored by chemicals (e.g., Glauber's salt) as the chemicals dissolve in the water of hydration with no temperature change.

This solar energy elective unit deals with thermal heat in detail and to a lesser extent with latent heat of fusion. Thermal heat is the least complicated and most commonly used type of solar heat storage.



Active or Passive?

1. Thermal Heat Storage

The factors used to calculate the quantity of thermal heat stored are:

a. mass of storage material
b. temperature change
c. specific heat capacity of storage material

or

a. volume of storage material
b. temperature change
c. volumetric heat capacity of storage material

The heat stored in a material or released from storage is calculated using the formulas.

$h = mc\,\triangle t$

or

$h = vc\,\triangle t$

h is the heat stored or released in kilojoules (kJ) or megajoules (MJ)
m is the mass in kilograms (kg)
c is the specific heat capacity in kilojoules per kilogram degree Celsius (kJ/(kg.°C))
$\triangle t$ is the absolute change in temperature in degrees Celsius (°C)
v is the volume in cubic metres (m^3)
c is the volumetric heat capacity in mejajoules per cubic metre degree Celsius ($MJ/(m^3.°C)$)

In passive solar collection systems solar energy is usually stored in walls (made of concrete, bricks, rock or water) or in containers (oil drums, culverts, plastic or glass jugs filled with water). The principle of these storage methods is to absorb heat (which would normally overheat the house) while the sun is shining and release heat during the night when the house would normally cool off.

Example:

Calculate the heat stored in the drum wall shown below if each of the 21 drums contains 200 L of water. The water temperature rises from 20°C to 35°C. Ignore the heat stored in the steel of the frum and in the steel framing.

From the solar energy data sheet: For water, $c = 4.19\ MJ/(m^3.°C)$ and $1\ kL = 1\ m^3$

Volume, $v = 21 \times 200\ L = 4.20\ kL = 4.20\ m^3$

Heat stored, $h = vc\,\triangle t$

$= 4.20\ m^3 \times 4.19\ MJ/(m^3.°C) \times 15°C$

$= 0.24 \times 10^3\ MJ$

$= 0.24\ GJ$

(This amount of energy is sufficient to provide about 25% of the space heating requirements of an average house when the outside temperature is -30°C.)

Notes:

1. The word specific means a per unit mass quantity. The word volumetric refers to a per unit volume quantity.
2. In practical terms, the volume of a heat storage material is a more important consideration than the mass. For this reason and the fact that the volume of a regular solid or container can be directly determined, the formula $h = vc\,\triangle t$ is more useful in most solar energy calculations.

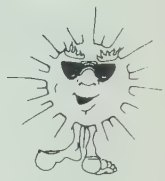
SOLAR HEAT STORAGE IN PASSIVE SYSTEMS
THERMAL HEAT STORAGE

Exercise:

After answering each of the next two questions, calculate the cost of an equivalent amount of electrical energy. Use your local electricity cost or assume a value of 1.0 ¢ /MJ.

1. How much heat is stored in a concrete Trombe Wall when the temperature rises from 20°C to 40°C? The wall measures 4.00 m by 6.00 m by 0.60 m thick.

2. Three steel cylindrical culverts 4.00 m tall and 1.00 m in diameter are filled with water to be used for passive solar heat storage. Calculate the amount of heat that can be stored in the water as its temperature rises from 20°C to 35°C. (Neglect the heat gained by the steel in the culverts.)



3. Heat storage in a concrete floor requires sufficient thermal mass so that the maximum temperature goes not become uncomfortable. The following question illustrates a typical situation.

   The illuminated area of a 0.24 m thick concrete floor measures 4.00 m by 6.00 m. The daily solar radiation falling on the floor is 7.1 MJ/(m^2.d), of which 40% is absorbed as heat. If the temperature of the floor is 18°C in the morning just before the sun rises and the maximum temperature is 24°, calculate the required thickness of the concrete floor.

Introduction to Heat Storage as Latent Heat of Fusion

The main disadvantage of water and concrete, the two most common *thermal heat storage* materials, is the large volume required to store practical amounts of heat. Latent heat of fusion is a particularly attractive form of heat storage because of the generally large amounts of heat stored per unit mass. For example, the latent heat of fusion of water ⟶ ice is 335 kJ/kg. Unfortunately this phase change occurs at the impractical temperature of 0°C. The challenge is to find an inexpensive chemical that readily undergoes a solid-liquid phase change at a reasonable temperature for solar heat storage and utilization.

Heat is stored or released depending on the direction of the phase change.

$$\text{solid} + \text{heat} \rightleftharpoons \text{liquid} \qquad \text{(at the melting point)}$$

The following equation is used to calculate the amount of heat stored or released by a given mass of a chemical at its melting point.

$h = mL$

- m is the amount of heat stored or released in kilojoules (kJ)
- h is the mass of the chemical in kilograms (kg)
- L is the specific latent heat of fusion in kilojoules per kilogram (kJ/kg). (See Solar Energy data sheet.)

Note: Mass is used here since small amounts in trays and containers are often used. The corresponding formula, $h = vL$, can also be used where convenient.

2. Heat Storage as Latent Heat of Fusion of Eutectic Salts

A heat storage material that fulfills most of the requirements stated above is the eutectic salt, Glauber's salt (sodium sulfate decahydrate, $Na_2SO_4.10H_2O_{(s)}$). Heat is absorbed at a constant temperature by the Glauber's salt as it changes from a solid to a liquid.

$$Na_2SO_4 \cdot 10H_2O_{(s)} + \text{heat} \rightleftharpoons Na_2SO_{4(aq)} \qquad \text{at } 32°C$$

Conversely, when the sun goes down and the air cools, heat is released by the sodium sulfate solution as it recombines with the water to become the hydrated solid (right to left in the above equation).

The cost (about 3.3¢/kg) of the Glauber's salt is not prohibitive and the melting point is not unreasonable for solar energy applications.

Glauber's salt is not without disadvantages as a widespread heat storage material.

a. Corrosion of metal containers may be a problem.
b. Solidification on the walls of the container reduces heat exchange and prevents mixing (with water), thus lowering the heat absorbed per unit mass. This problem can be reduced by adding silicon dioxide to prevent separation of the solution.
c. Irregular crystal formation during successive heating-cooling cycles tends to lower the efficiency of the salt dramatically.
d. After a period of time, Glauber's salt has a tendency to remain liquid below 32°C and not give up its heat when needed.

Glauber's salt (and more complex eutectic mixtures) hold sufficient promise that research is actively continuing to overcome or control the problems listed above.

Example of a Latent Heat of Fusion Calculation

Calculate the heat absorbed by 25.0 kg of Glauber's salt changing from solid to liquid at 32°C. What temperature change would 25.0 kg of water have to undergo to store the same quantity of heat?

From solar energy data sheet: $L = 242$ kJ/kg, (for Glauber's salt) $c = 4.19$ kJ/(kg·°C) (for water)

$h = mL$

$= 25.0\,\text{kg} \times 242\,\text{kJ/kg}$
$= 6.05$ MJ

The heat absorbed by 25.0 kg of Glauber's salt is 6.05 MJ.

$h = mc\,\triangle t$

$\triangle t = \frac{h}{mc}$

$= \frac{6.05 \times 10^3\,\text{kJ}}{25.0\,\text{kg} \times 4.19\,\text{kJ/(kg·°C)}}$

$= 57.8$°C

The temperature change required for 25.0 kg of water would be 57.8°C.

Exercise on Thermal and Latent Heat Storage

The primary advantage of latent heat storage is the large amount of heat that can be stored in a small volume. In the following questions a comparison will be made of several examples of heat storage. For thermal heat storage, assume a practical temperature change of 10°C. Use the answer from Question 1 to solve the remaining questions.

1. Calculate the amount of solar heat stored by 1.00 m^3 of Glauber's salt undergoing a phase change.

2. Calculate the equivalent volume of water.

3. Calculate the equivalent volume of concrete.

Purpose:

To compare the solar heat storage characteristics of five different materials.

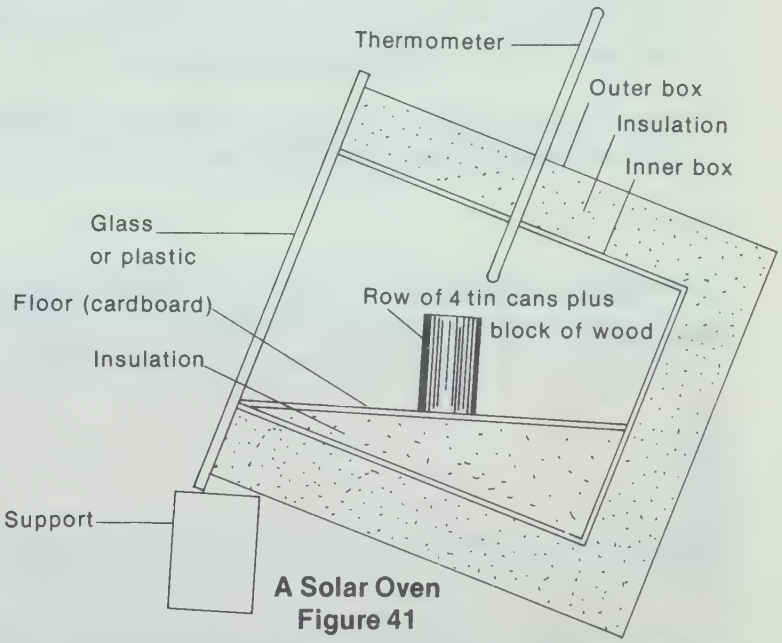
Materials:

Prelab - Solar Oven

2 - cardboard or styrofoam boxes such that one is approximately 5-10 cm larger than the other in each dimension. (One thick styrofoam box would suffice.)
1 - piece of cardboard to serve as a false floor
1 - sheet of glass or clear plastic large enough to cover the front of the larger box
- insulation (fiberglass)
- flat-black spray paint
- support block
1 - roll masking tape
1 - thermometer (-10 to 110°C)

Lab Materials:

4 - small tin cans painted flat black on the outside (384 mL soup cans are satisfactory)
5 - 2 L milk cartons
6 - thermometers (-10 to 110°)
1 - block of wood painted black (384 cm^3)
- sand
- small stones
- thermal gloves
- water
- ready mix concrete
1 - stapler
1 - roll masking tape
1 - watch or clock
2 - sheets of graph paper per student
1 - 150 W flood lamp if experiment is to be done indoors



A Solar Oven
Figure 41

Procedure:

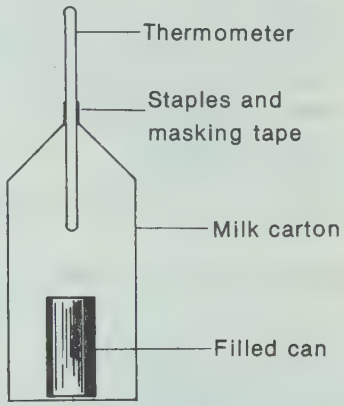
A. Construction of a Solar Oven

1. Construct a solar oven by placing the small box inside the large one and filling the space between the boxes with fibreglass insulation.
2. Tilt the oven so as to receive the sun's rays at right angles to the glass. Install a level floor as shown in Figure 41 above.
3. Paint the interior of the oven flat black. (The exterior of the four tin cans plus block of wood could also be painted at this time.)
4. Insert a thermometer through the oven wall and tape it in place for convenient reading from outside the oven. (The thermometer must not be in the direct sunlight.)
5. Use masking tape to hinge the glass or plastic cover to the top of the box.

B. Lab Procedure

1. Prepare the four blackened tin cans by filling with equal volumes of water, sand, rock and concrete.
2. Place the four filled cans and the block of wood in the solar oven. Put the glass cover in place. Locate the oven for maximum solar heating and leave the contents to be heated for an hour or more.
3. Leave samples in the solar oven for 1-2 h after oven has reached its maximum temperature. (Read and record the temperature in the oven at 10 min intervals if evidence of the oven's effectiveness is desired).
4. Quickly transfer each of the four cans and the block of wood into an upright, labelled milk carton and seal each carton with a thermometer equal distance through the top for convenient reading.

   (Seal the carton by closing the flaps with the thermometer between. Staple the flaps together then apply masking tape for an airtight seal and support of the thermometer.)



Heat Storage Unit
Figure 42

5. Record the room (ambient) temperature.
6. Read and record the temperature in the milk cartons at 5 min intervals for the first 40 min and at 10 min intervals for the next 80 min.

Observations:

Ambient temperature =_____°C Initial time =_____

Material / Time	5	10	15	20	25	30	35	40	45	50	60	70	80	90	100	110	120
Water																	
Sand																	
Rock																	
Concrete																	
Wood																	

Postlab Exercise:

1. Plot a separate graph of temperature difference (i.e., the temperature inside the carton minus ambient temperature) versus time elapsed for each of the five milk cartons.
2. Make a bar graph showing the amount of heat lost by each storage unit during the 2 h of observation. (Use the approximate area under the temperature difference versus time graph to obtain the heat lost values required.)
3. Make a bar graph showing the amount of heat lost by each of the storage units during the first 20 min of observation.
4. List the variables which were controlled in this lab.

Conclusions:

Rank the five heat storage materials according to the characteristics listed below. Use a ranking of 1 as the best in the category.

Characteristics of Material	Water	Sand	Rock	Concrete	Wood		
1. Effectiveness for long time intervals (2 h)							
2. Effectiveness for short time intervals (20 min)							
3. Cost of Material							
4. Convenience of Material							

5. Use the sum of the rankings of each material to arrange the five heat storage materials from overall best to overall worst.

6. What assumption is made when comparing materials using the sum of the rankings? Comment on the validity of this assumption.

7. Rank the five materials from highest to lowest volumetric heat capacity. (See the solar energy data sheet.) How does this order compare with the results obtained?

8. In addition to the ability of a substance to store heat, what other physical property is important?

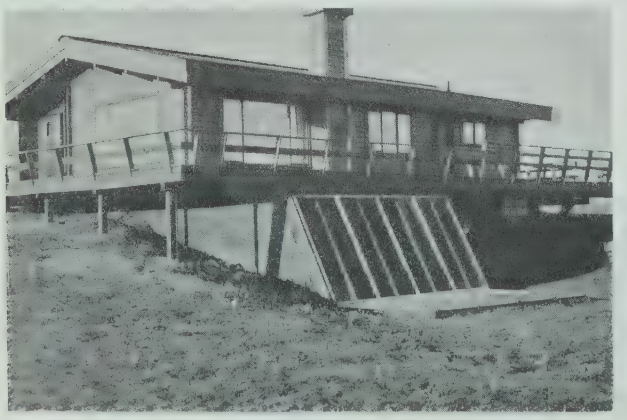
9. In actual home heat storage systems, the heat storage system may not be in a central location. This may result in parts of the house (e.g., the north end) being somewhat cooler. Without changing the design of the house, how could this problem be eliminated?

Introduction to Active Systems

The earth and windowed dwellings are passive solar collectors. Passive systems are in general more natural, less sophisticated, less mechanical and less costly. Active systems are more complex, more mechanical and more costly, but can also be more convenient and more efficient. The active system is usually most different from the passive system in that the active system mechanically delivers excess solar energy to storage during sunny periods. The stored energy can then be mechanically moved through the dwelling when required.

There is a debate being waged between pro-passive and pro-active supporters. On the one side some solar experts claim that active systems will never be as economic as a competitive heating system in most parts of the country. They claim that the media concentrates on active systems and either build false, costly expectations or criticize solar systems with no mention of passive systems at all. Pro-passive experts claim that governments and politicians promote the high technology of active systems to promote employment in industry and in general because of the technological orientation of modern society. On the other hand, pro-active experts say that fossil fuels will rise so high in price that their systems will be economic in the long run. All solar supporters say that solar systems would be even more reasonably priced if the solar industry was given tax breaks equivalent to the tax incentives given to other energy industries (e.g., oil companies).

The cost of active solar systems may seem large but the capital cost must be amortized over five to fifteen years when making comparisons to current and future fuel bills. Since the cost of sunlight is zero and the cost of running pumps, fans and electronic controls is similar to a conventional heating system, the whole system can be paid for with similar maintenance and mechanical operating costs to a conventional system. However, the cost of fossil fuels will continue to rise and will make solar systems more and more cost attractive. (Similarly, CANDU nuclear power plants in eastern Canada are currently producing electricity at one-half the cost of conventional power plants in that area in spite of the high capital cost for nuclear power plants. The inexpensive uranium fuel more than compensates for the high initial capital cost of equipment.) A second factor that will eventually make active systems more economically competitive with fossil fuels will be the mass production of proven active solar systems. The mass production of active systems will decrease the effect of inflation on the unit cost. Another factor that will make active systems relatively less costly will be the increase in quality in terms of longevity. An active component is less costly the longer it lasts.

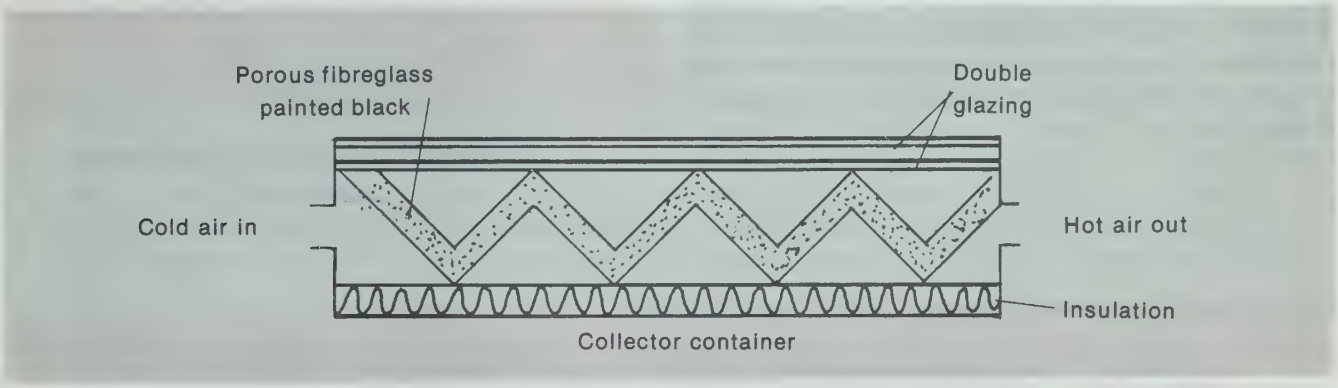


Active Air Collectors

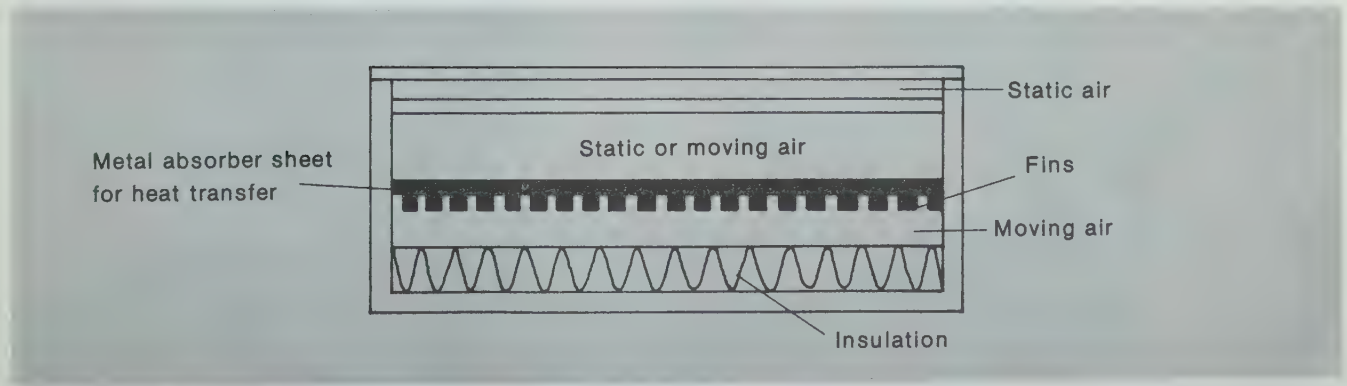
Active air collectors use air as the transport fluid and work on the same absorption principles as the passive collectors described earlier. Many active air collectors are retrofitted or built-in on the roof of a dwelling for convenience and for maximum exposure to sunlight. Since hot air naturally rises, a low speed blower must be used to circulate the air from the collector *down* to the heat storage unit or dwelling. The blower may be an extra expense or may be the regular fan which is part of the back-up furnace. If the air collector can be placed below the storage unit as in the case of a house on a slope then the heated air will thermosiphon to storage.

Before heat may be exchanged to a dwelling, the warm air direct from the collector or from storage must be at least 5°C greater than the air temperature of the dwelling. A thermostat which senses the temperature in the collector, in storage, and in the dwelling turns on the circulating fans when required.

Within the collector, the surface area contact between the circulating air and the absorbing surface needs to be increased to an optimal level. The surface area is increased by using porous fiberglass, fins, screen, or aluminum cans. Air collectors are generally double glazed with black collecting surfaces and with insulation on the back and sides.



**Side View of Figreglass Matrix
Air Collector
Figure 43**

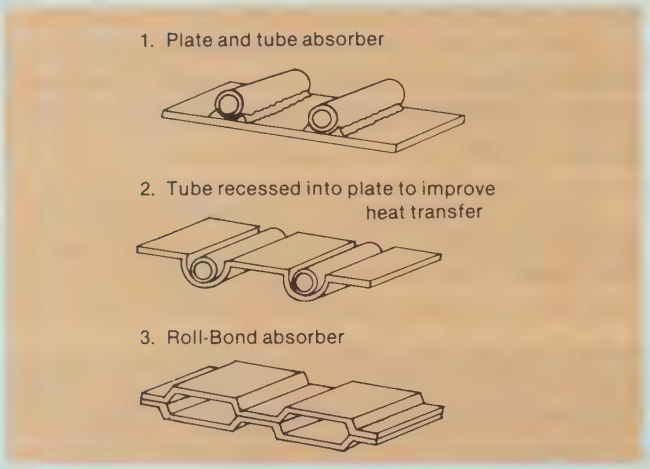


**End View
Cross Section of Flat Plate
Active Air Collector
Figure 44**

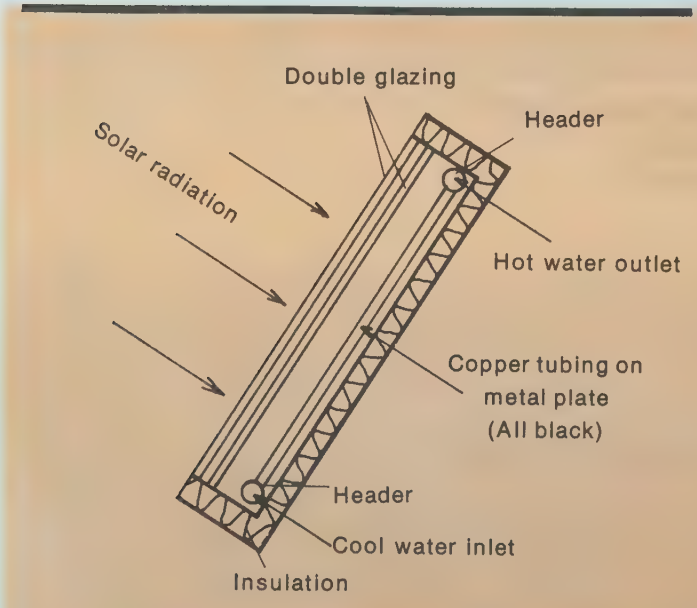
Active Flat Plate Liquid Collectors

Active liquid collectors differ from passive liquid collectors in that the liquid from the collector is *pumped* through finned-pipe heat exchangers in rooms in the dwelling or to heat storage units (usually in the basement) or a swimming pool or a hot water heater. Usually the liquid used is water. In cold climates an antifreeze such as ethylene glycol is added to the water. When an antifreeze is used, the warm water from the collector cannot be used directly for swimming or domestic hot water. The antifreeze solution must be passed through a heat exchanger to heat the domestic water supply.

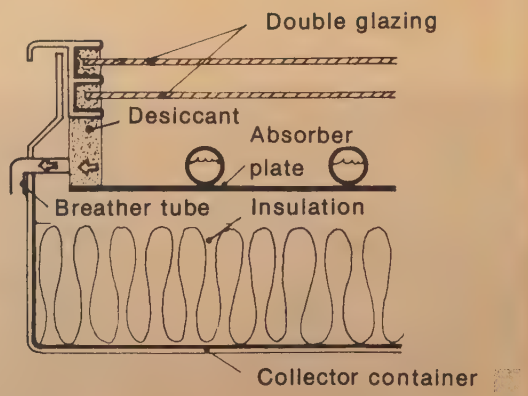
The water (liquid) collectors usually move the water from the bottom to the top of the collector. (An exception is the trickle system where water trickles down over the hot collector surface.) There are many different ways of moving the water through the collector; some methods are shown in Figure 45. The tubing type collectors usually use black painted copper pipe soldered to a black heat-conducting absorption plate. There must be good conduction contact between tube and plate because the plate is the collector. The collectors are generally double glazed, painted black and insulated in the back sides.



Different Types of Absorber Plates
Figure 45



Side View of Active Liquid Collector
Figure 46



Cross Section of Flat Plate Collector
Figure 47

Efficiency of Active Collectors

The efficiency of an active collector is the ratio of the heat energy transported out of the collector to the solar energy striking the collector glazing. Consumers should beware of possible exaggeration of collector efficiencies by some manufacturers of collectors. The efficiency of an active collector is affected by the:

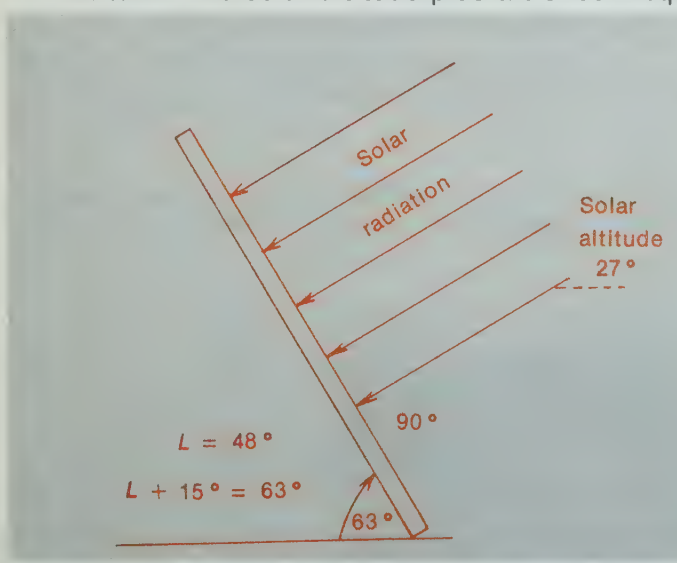
1. tilt or orientation of the collector
2. glazing (glass or plastic cover)
3. collecting surface and inter-glazing medium
4. heat loss by the collector
5. collector fluid

1. The Collector Tilt

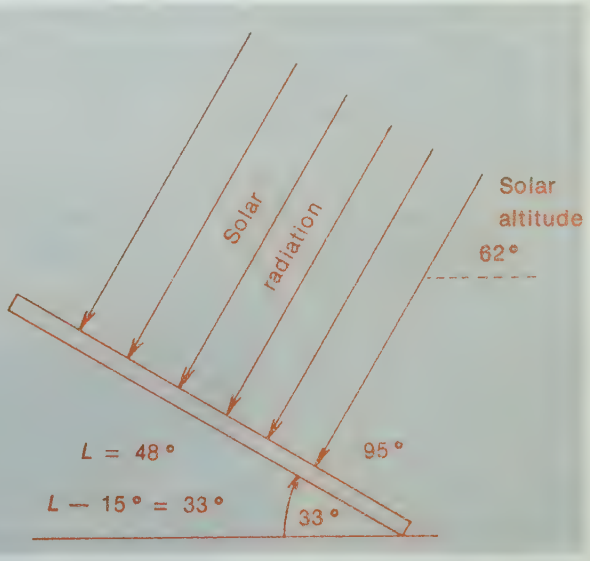
The tilt of the collector can be an important variable in determining the efficiency of a collector. A nonperpendicular angle to the sun will decrease the effective area of the collector and may result in greater reflection from the glazing. Ideally the collector should be perpendicular to the sun throughout the day. To track the sun, a sun path chart would have to be followed for each day of the year for a particular latitude. Such a set-up would add considerably to the cost of a solar installation.

A practical compromise is to fix the orientation of the collector to the south. A variation of 15° from the south makes only a small difference in the amount of solar energy collected. The tilt of the collector should be near perpendicular during the heating season. Again, a sun path chart for the latitude is useful, but a rule-of-thumb often used is that the tilts (from the horizontal) should be the latitude(L) plus 15°. If the latitude is 48°, then L + 15° is 63°. Since the approximate average solar altitude during the heating season at noon(as obtained from a sun path chart) is about 27°, the collector would be about perpendicular (63° + 27° = 90°) to the sun as required.

For solar cooling or swimming pool heating during the summer, the tilt should be about L-15°. For L = 48°, the summer tilt should be about 33° which suits the summer solar altitude at that latitude. The solar altitude plus tilt should equal approximately 90°.



Tilt for Heating Season at 48° Latitude (L + 15°)
Figure 48

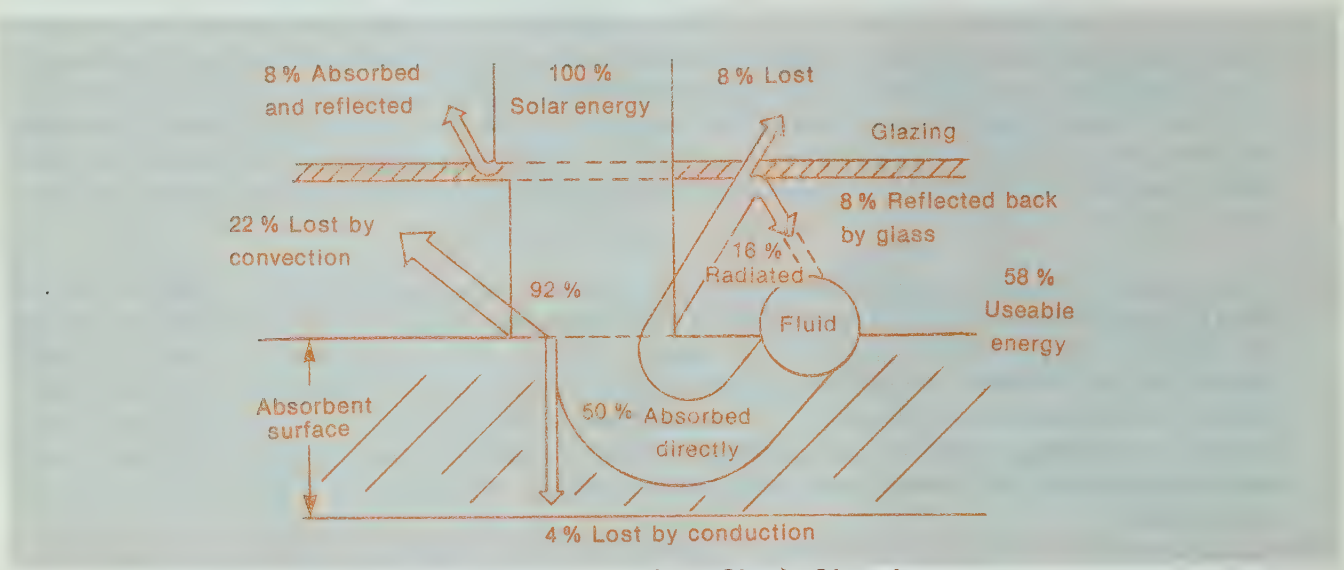


Tilt for Summer at 48° Latitude (L-15°)
Figure 49

1. Glazing

The transmission coefficient of the glazing materials (listed on the data sheet) will affect the amount of perpendicular solar radiation which passes through the glazing. The number of layers of glazing will not only affect the collecting efficiency by reducing the collection but also by reducing the loss of solar heat energy. The reduction in the loss of energy results from (1) preventing loss due to convection currents originating from the collector surface,(2) producing a greenhouse effect inside the collector and (3) keeping the wind, rain, snow and cold air away from the collecting surface (i.e., insulating the collector surface). Typical RSI-values for glass, single and double glazing are 0.16 and 0.35 (m^2.°C/W) respectively.

Figure 50 shows typical losses for a single glazed liquid collector and illustrates the role of the glazing in minimizing losses.



Typical Losses from Single Glazed Collector with Selective Coating
Figure 50

If 90% of the solar energy passes through single glazing, then 90% of 90% or 81% will pass through double glazing. Fortunately, the main heat components (IR and visible) pass through the glazing readily. UV radiation is not transmitted readily (thus the inability to get tanned or sunburned behind glass).

A complicating factor for both passive and active systems is the decrease in the transmission coefficient for nonperpendicular angles. Some active collectors try to counter this problem by using a curved glazing (see Figure 51).

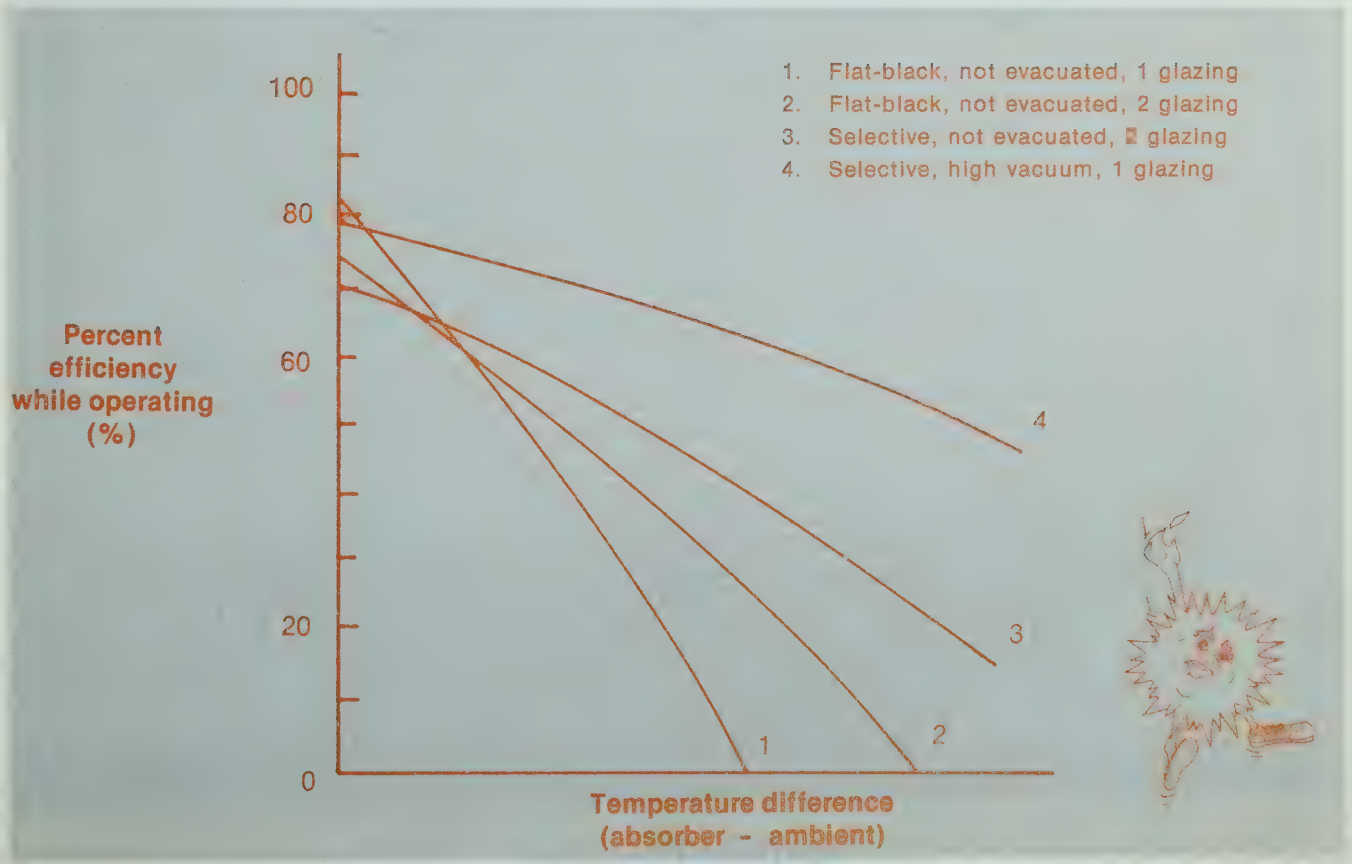
An Active Collector with Curved Glazing
Figure 51

3. Collecting Surface and Inter-glazing Medium

The medium between the layers of glazing or between the collecting surface and the glazing is typically air. The air is heated by the collecting surface by conduction and transmits the heat to the glazing by conduction and convection. The glazing transmits heat to the outside air by conduction. The loss of heat energy by this means may be reduced by using a vacuum instead of air to fill the space between the glazing.

The collecting surface is usually painted with flat black paint with the assumption that the same material which absorbs visible light also absorbs IR radiation. Research with selective coatings has provided data concerning the absorptivity and emissivity. The best coatings will selectively absorb short wavelength radiation but not re-emit long wavelength IR radiation.

Figure 52 below shows the relative performance of different collecting surfaces and interglazing medium. Notice that a flat-black collector with one glazing is highly efficient at a low temperature difference above ambient, but as the temperature difference increases its efficiency rapidly goes down. On a very cold day this system could not be used as it would radiate heat to the environment. On the other hand, double glazed collectors are less efficient than single glazed at low temperature differences because of light transmission losses but at higher temperatures are more efficient because of their added insulating factor to heat losses. The most efficient system at even high temperature differences to the ambient is the high vacuum system from which conduction losses are very small.



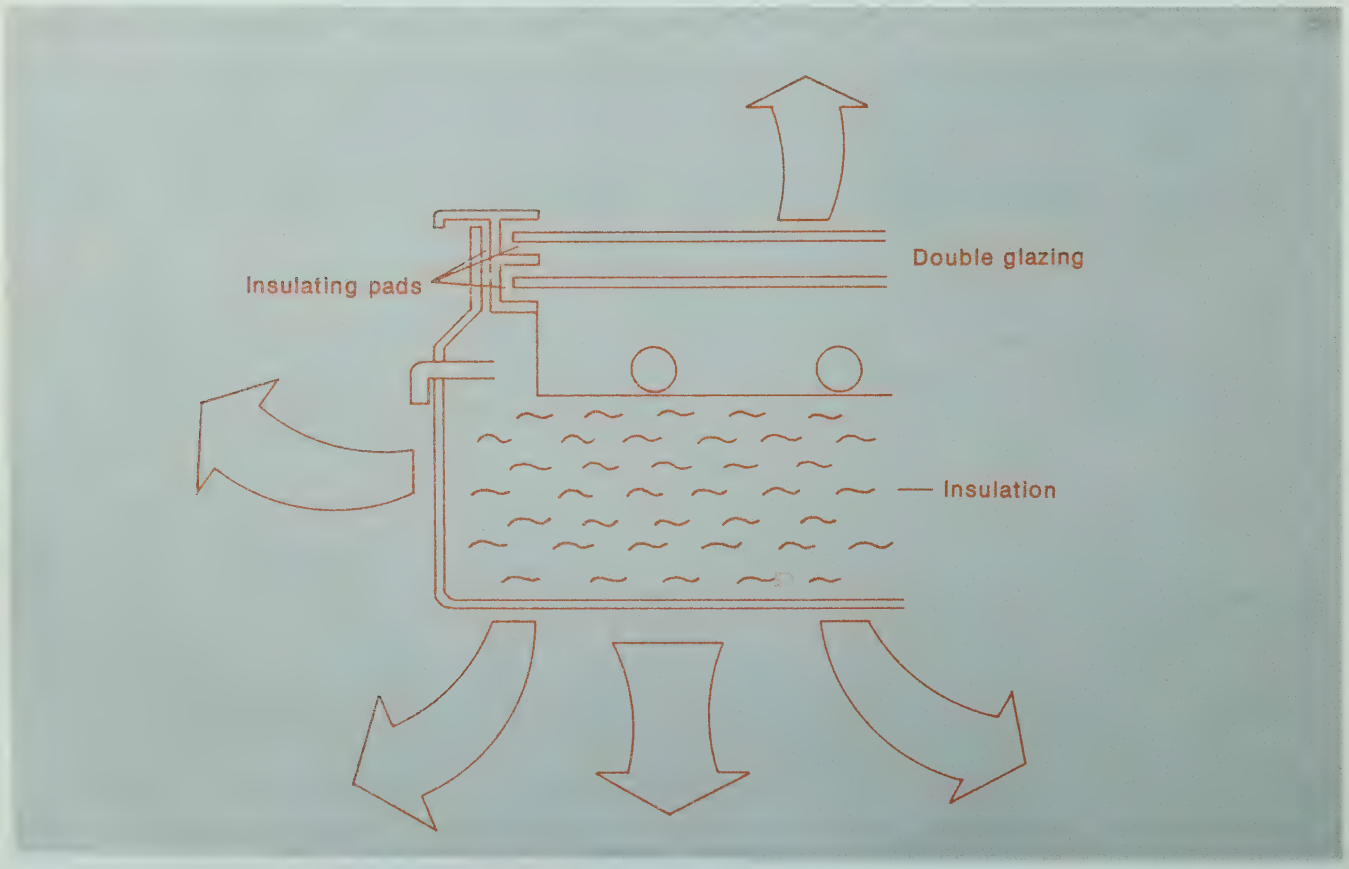
Efficiency of Collecting Surface and Inter-glazing Medium
Figure 52

4. Heat Loss by the Collector

An active collector is generally insulated from the back and sides by insulation and from the front by single or double glazing and perhaps a vacuum. The double glazing reduces the input of solar radiation but has a net positive effect by reducing heat loss.

An increase in heat lost (and thus a decrease in the efficiency of the collector) will result as the temperature difference between the inside and the outside of the collector increases. The collector temperature can be kept at a desireable level by adjusting the rate of flow of the collector fluid (liquid or gas). Thermostatically controlled valves are necessary to adjust the flow of the fluid from the collector to the dwelling and/or to storage. Another variable which may be adjusted when initially building the collector is the surface area between the collector and the fluid. The greater the surface area interface, the greater the rate of heat transfer between the collector and fluid (and the smaller the chance of overheating).

Once the fluid temperature is several degrees greater than the dwelling, swimming pool or heat storage temperature the pump is activated. In general the collector fluid should only increase in temperature by about 5°C each time the fluid passes though the collector. In cold weather the collector fluid must first be allowed to rise to 5°C above the dwelling and/or storage temperature. After reaching the required starting temperature the flow rate must be adjusted either to keep a constant temperature for direct heating or eutectic salt heat storage, or to allow the temperature to gradually increase for rock or water storage systems. The higher the collector temperature is above the ambient temperature, the greater will be the heat loss.



Heat Loss By a Collector
Figure 53

5. The Collector Fluid

The collector fluid must be able to transfer the heat from the collector to the dwelling and/or to storage in an efficient manner. If air is the transfer fluid, then the air may be used directly to heat the dwelling. If space heat is not required, the air may be used to heat rock or eutectic salt or future materials in storage systems. Air has a low specific heat capacity (and thus requires a more rapid flow rate than liquids, otherwise it overheats and efficiency falls) but does not corrode or freeze.

If water is used as the transfer fluid, then the water may be used directly in a hot water heating system to heat the dwelling. When water is the transfer fluid, water is generally also the storage fluid, although hybrid systems with a combination of water collection and rock storage exist. Water has a relatively high specific heat capacity (thus requiring a slow flow rate). However, water will corrode the pipes and storage unit will freeze. To overcome the corrosion and freezing problem, anticorrosion chemicals, along with an antifreeze such as ethylene glycol, are added to the water.

To save on the amount of ethylene glycol that has to be purchased and to allow for heating of domestic water, a heat exchanger is generally used to transfer the heat to the storage unit or to the domestic water. (More details are given in the active storage section.)

Table 3
Performance Characteristics of Heat Transfer Fluids

Transfer Fluid	Specific Heat Capacity kJ/(kg. °C)	Freezing Point (°C)	Other Significant Properties
Water	4.19	0	b.p. 100°C
50% Water-Ethylene Glycol	3.5	-35	b.p. 110°C Toxic and Corrosive
50% Water-Propylene Glycol	3.6	-31	b.p. 110°C Corrosive
Paraffinic Oils	2.1	-7	b.p. 190°C

Exercise on Active Collection of Solar Energy

1. What is the difference between an active and a passive solar collector?

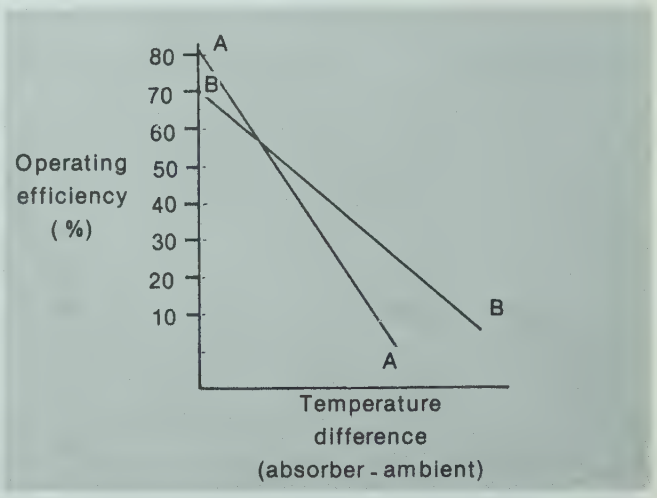
2. What cost factors must be considered when comparing heating with fossil fuel and heating with active solar collectors?

3. Sketch a labelled cross-section of an active flat plate liquid solar collector.

4. Describe briefly how an active solar collector works.

5. List five factors which affect the efficiency of an active solar collector.

6. The graphs A and B at right are plots of efficiency versus temperature difference (absorber-ambient) for two flat-black collectors. Which represents a double glazed collector and which a single glazed collector? Explain the glazing effect on low and high temperature efficiency.



7. Calculate the efficiency of a retangular solar collector 5.00 m by 2.00 m which has solar radiation of 10.2 MJ/(m^2.d) incident on it. In a day the collector sends to storage 45.3 MJ of heat.

8. Calculate the optimum tilt (from the horizontal) of a collector for December 21 and for June 21, if it is to be set up at latitude 40°.

Introduction to Solar Heat Storage in Active Systems

The usual objective of an active system is to supply a significant portion of the space heating requirements of a house. However, the high cost and complexity of these systems may prevent any widespread use. At the moment active systems for home space heating are largely experimental and generally not considered to be economical. On the other hand, the use of active systems for domestic water heating and swimming pool heating is more widespread and can be made economical.

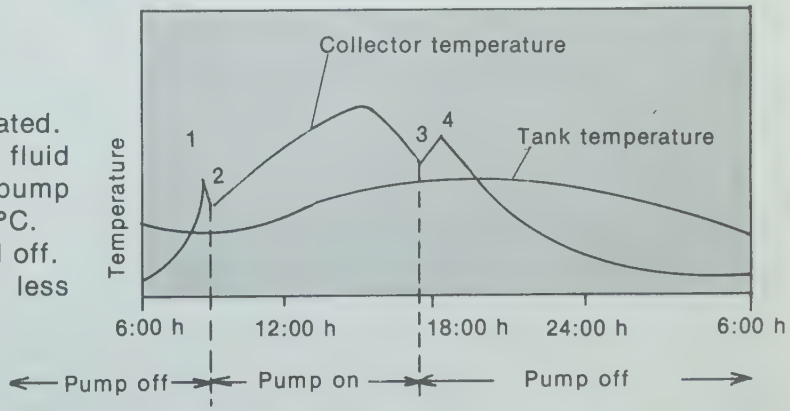
In active systems, the collectors convert the solar radiation into heat which is then transferred to the collector fluid. Fans, pumps and/or heat exchangers are used to transfer the heat into the storage medium. A distribution system moves heat from storage into the house when activated by an ordinary room thermostat. Active solar systems generally have a conventional heating system as a back-up.

Active Liquid System
Figure 54

Operating Cycle of an Active System

In active solar systems a special thermostat, called a differential thermostat, is required. This device measures the temperature difference ($\triangle t$) between the collector and the storage tank. The pump or fan is turned off and on at preset temperature differences. Figure 55 and the following explanation describes a typical operating cycle. (The numbered statements refer to the numbers on the graph.)

1. When $\triangle t$ = 11°C, the pump is activated.
2. Circulation of the cooler storage tank fluid lowers the collector temperature. The pump remains on unless $\triangle t$ drops below 2°C.
3. When $\triangle t$ = 2°C, the pump is turned off.
4. The temporary rise in temperature is less than 11°C and the pump remains off.

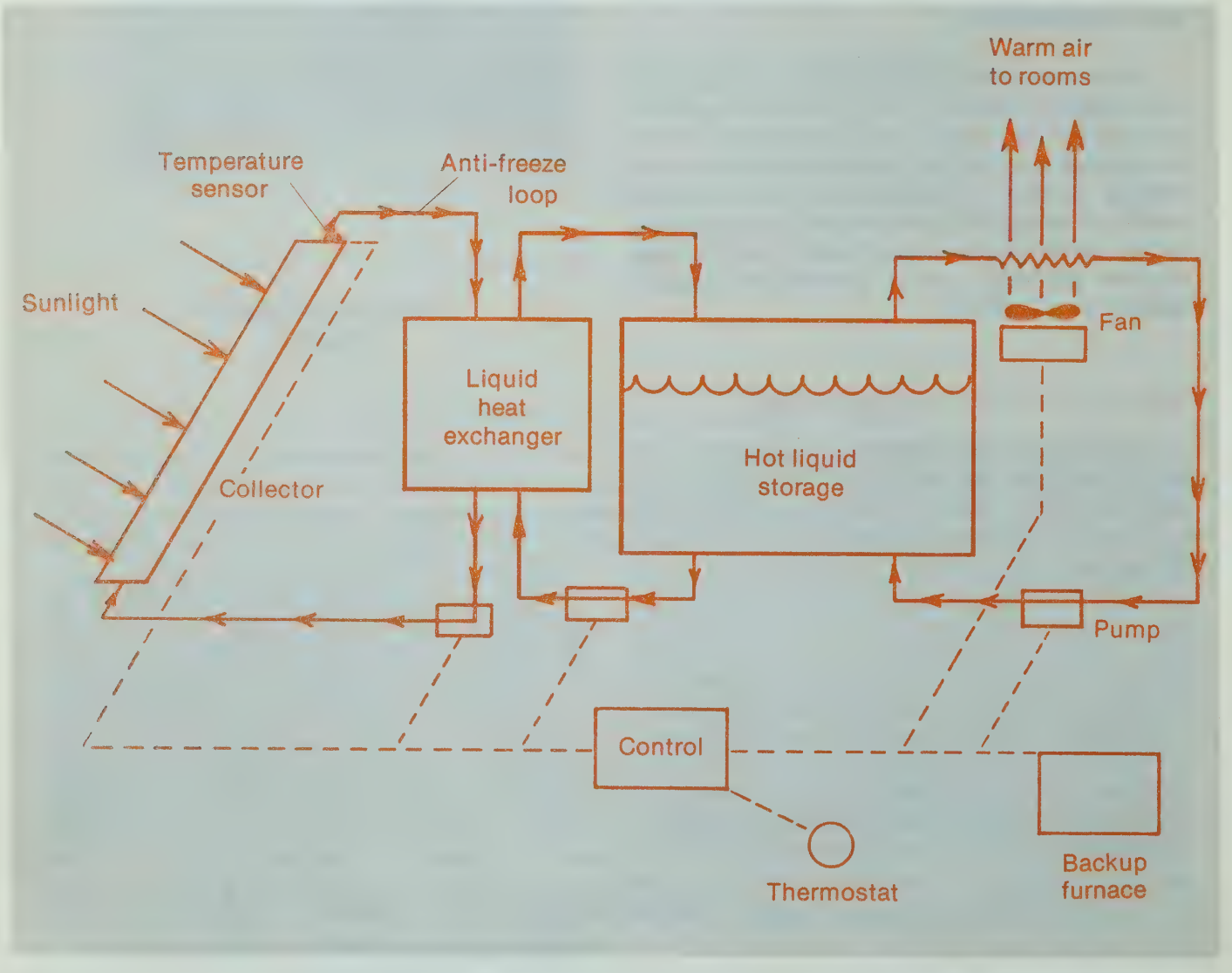


Typical Operating Cycle of an Active System
Figure 55

Thermal heat storage in water or rocks is the main type of heat storage presently employed with active systems. Heat storage as latent heat of fusion of eutectic salts is, as in passive systems, still largely experimental. In thermal heat storage, the choice of water or rocks as the heat storage medium depends largely on the choice of the collector fluid. If water (or a water/antifreeze solution) is used in the collectors, then water will likely be the storage material. Rock storage is generally used with air collectors. The main consideration is to reduce the size and number of heat exchangers to increase the efficiency of the system.

Thermal Heat Storage in Water

Water is a good heat storage material. It is cheap, readily available, nontoxic and has a relatively high heat capacity. Ideally water would be used both as the collector fluid and as the heat storage medium. Unfortunately, water freezes at 0°C and, therefore, cannot easily be used in most of North America during the winter season. Except for the automatic drain-down collectors, the collector fluid is usually a water-antifreeze solution. This necessitates liquid-liquid heat exchangers to transfer heat energy to the water in the storage tank. Unless hot water radiators (or ceiling or floor pipes) are used for space heating, an additional liquid-air heat exchanger is required. A typical active liquid system is shown in Figure 56 below.

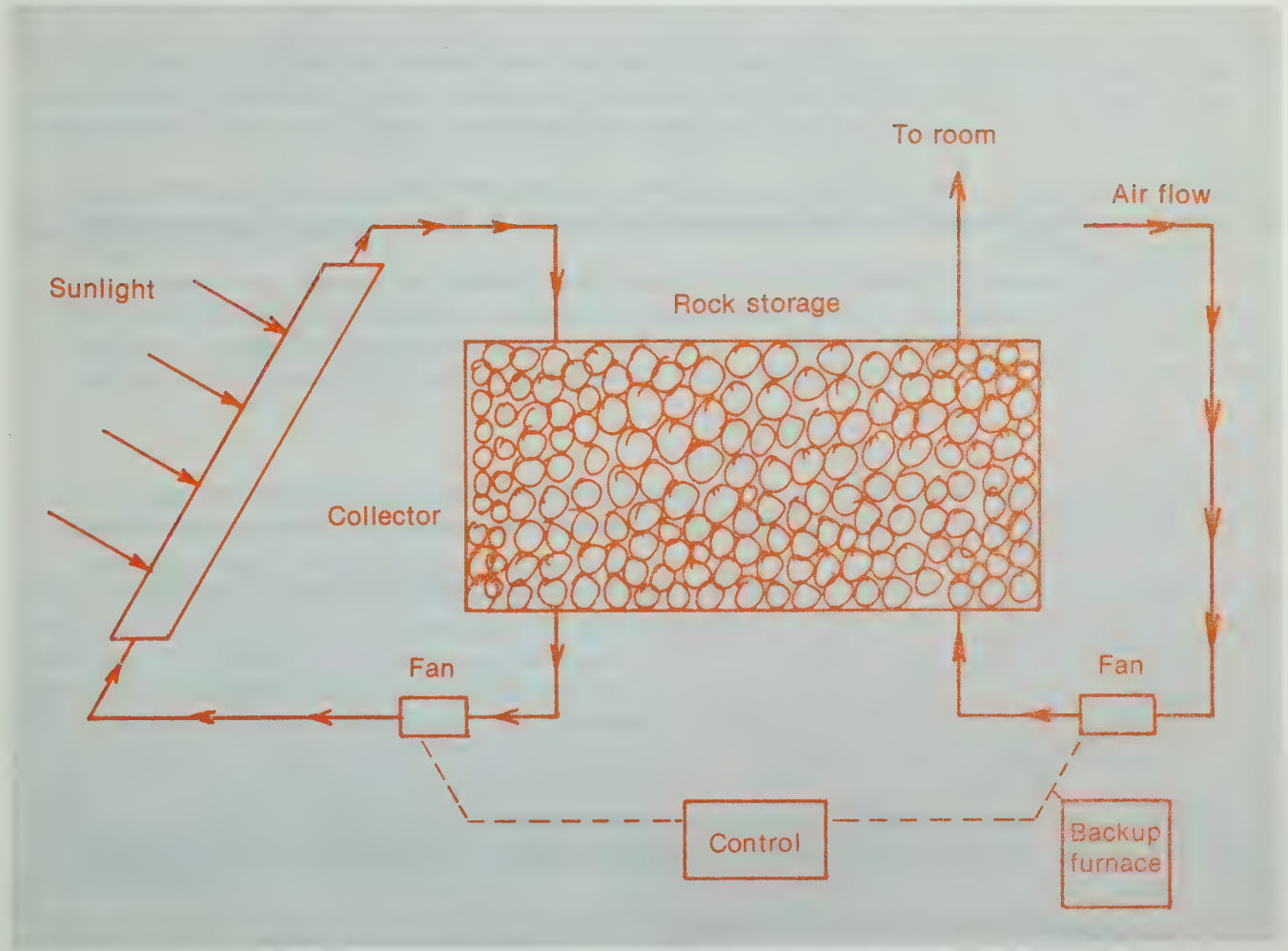


Active Liquid System
Figure 56

Thermal Heat Storage in Rock

For active air systems, small rocks (3 to 6 cm in diameter) are the most widely used storage material. (Small continers of water or eutectic salts are used to a much lesser extent in active air systems.) In general, the rocks should be large enough to allow a good circulation of air but small enough to insure good heat transfer. About a 30% void (empty space) is usually required for good air circulation and a very large storage bin for adequate heat storage.

Rock has a lower heat capacity and a higher density than water. The resultant effect of these competing factors makes rock a less compact heat storage material compared to water. Rock stores only 1.92 MJ/(m^3·°C) compared to 4.19 MJ/(m^3·°C) for water. When the 30% void is taken into account water stores about 2.73 times as much heat per unit volume of storage. Another disadvantage of rock is its low heat conduction rate (i.e., it takes longer to heat up). On the other hand, active air systems using rock storage are generally simple in design and plumbing. (Compare Figure 57 below to Figure 56.)



Active Air System—Rock Storage
Figure 57

Exercise:

An insulated rectangular tank, 7.50 m x 7.50 m x 2.20 m high, is to be used as a storage container. Use this information to answer the next four questions.

1. Calculate the total volume of the tank.

2. If the tank contains rock with a 30% void, what is the actual volume of rock in the tank?

3. How much heat would be stored in the tank when filled with rock with a 30% void and the temperature rose from 20.0°C to 40.0°C?

4. How much heat would be stored in the tank when filled with water and the temperature rose from 20.0°C to 40.0°C?

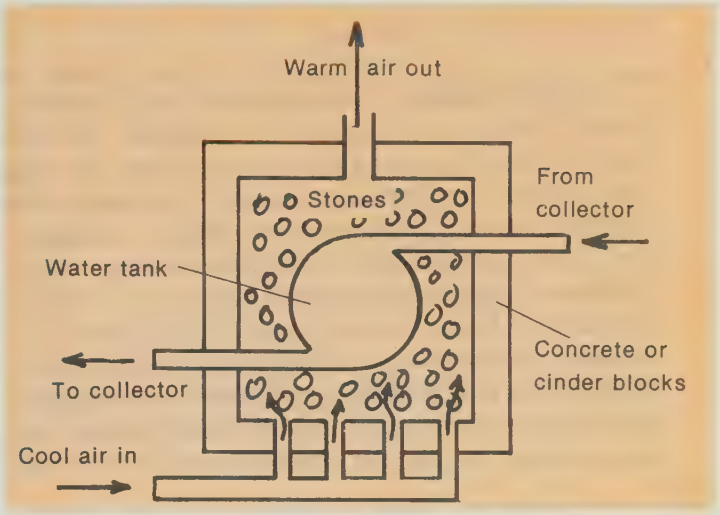
An active liquid system is designed to collect 250 MJ/d in January and to store the heat in water within a temperature range of 25.0°C. Use this information to answer the next two questions.

5. Calculate the volume of water required to store the solar energy collected in one day.

6. Use the local heating costs to determine the cost savings for the month of January. (If local costs are not available use 1.0 ¢/MJ for electrical heating and 0.2 ¢/MJ for gas heating.)

Water-and-Rock Storage

A hybrid heat storage system combining water and rock storage is shown in Figure 58. Water (or water/antifreeze solution) is used as the transport material from the collector and as a storage medium. The rocks provide extra heat storage and also act as a cheap, effective heat exchanger. With a slow circulation of room air and the large surface area of the rocks, low storage temperatures (about 25°C) can be used to heat the house. This system combines the high storage density of water with the even and rapid heating of a forced air space heating system.



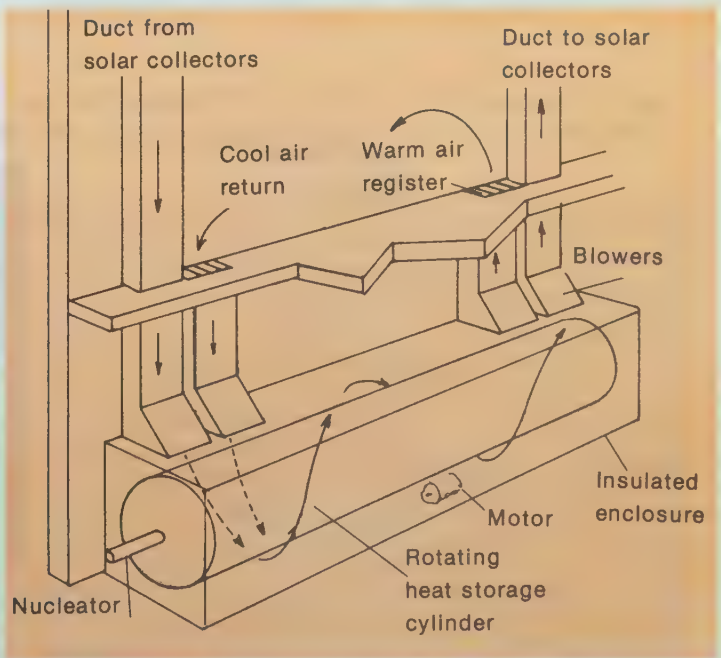
Heat Storage System Using Water-and-Rock Storage
Figure 58

Heat Storage As Latent Heat of Fusion

Eutectic salts, such as Glauber's salt, are the only real alternative to rocks and water for active air systems at the present time. (Paraffins have been tried, and zeolites are just now being tried as alternatives.) The use of Glauber's salt has two main advantages over water, concrete or rock.

1. *Compactness:* Over practical temperatures, ranges of about 10°C, 1 m^3 of salt stores as much heat as 8 m^3 of water or 17 m^3 of concrete. (See volumetric heat capacity values on the data sheet.)
2. *Low Temperature Operation:* Glauber's salt stores heat at a constant temperature of 32°C. This low temperature makes containers easier to insulate and results in a lower heat loss. In cold climates, the temperature of the transfer fluid can be relatively low, while for rock or water the transfer fluid temperature must keep increasing or else the water or rock tank must be very large.

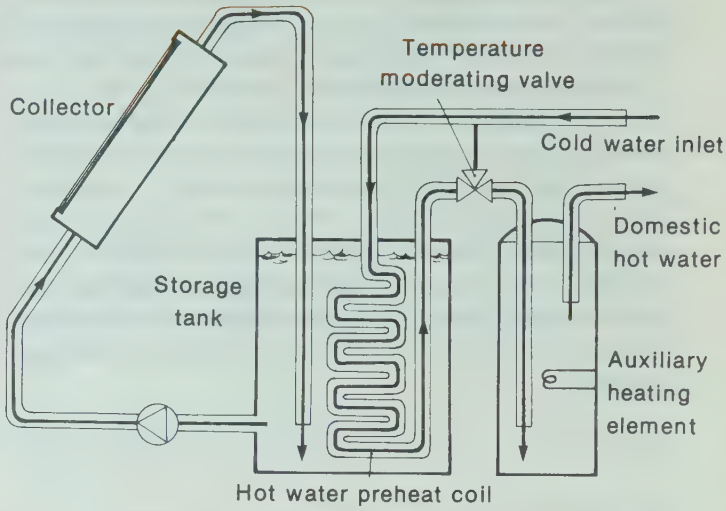
The disadvantages of heat storage as latent heat of fusion was discussed in detail in the earlier section, Solar Heat Storage in Passive Systems. Figure 59 illustrates an experimental system that hopes to overcome these problems. The nucleator contains chemicals to promote crystal growth. Turning the heat storage cylinder at about 3/min, mixes the contents to keep the temperature uniform. This rotation prevents an insulating growth of crystals on the inner walls of the container.



Eutectic Salt Heat Storage System
Figure 59

Domestic Water Heating

Space heating requirements vary tremendously from one season to another. In the summer the demand is almost zero and during the winter the demand usually exceeds the capabilities of a typical active system. Domestic hot water heating, on the other hand, is in constant demand throughout the year. A typical system such as the one shown in Figure 60 is smaller, simpler and usually more economical than active space heating systems. Compared to an electric water heater, a solar water heater can save enough to pay for itself within a few years.

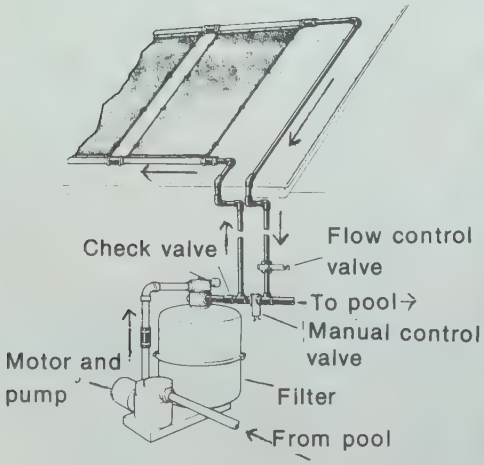


Domestic Water Heating System
Figure 60

Swimming Pool Heating

The heating of swimming pools is an ideal application of solar energy and usually one of the simplest. The storage tank, pumps and some of the plumbing are already in place and a simple inexpensive, home-made collector can easily be added. The use of an pool cover can greatly increase the efficiency and economics of the system.

In California it is illegal to heat a new swimming pool with natural gas so solar pool heaters are the only practical alternative. Similar laws will be enacted in other states and provinces as fossil fuels become more scarce.



Swimming Pool Heating System
Figure 61

Solar Heated Swimming Pool
Figure 62

Overview Exercise:

Briefly explain how each of the following terms can contribute to the collection and/or storage of solar energy.

1. orientation of house

2. landscaping

3. attached (or integrated) greenhouse

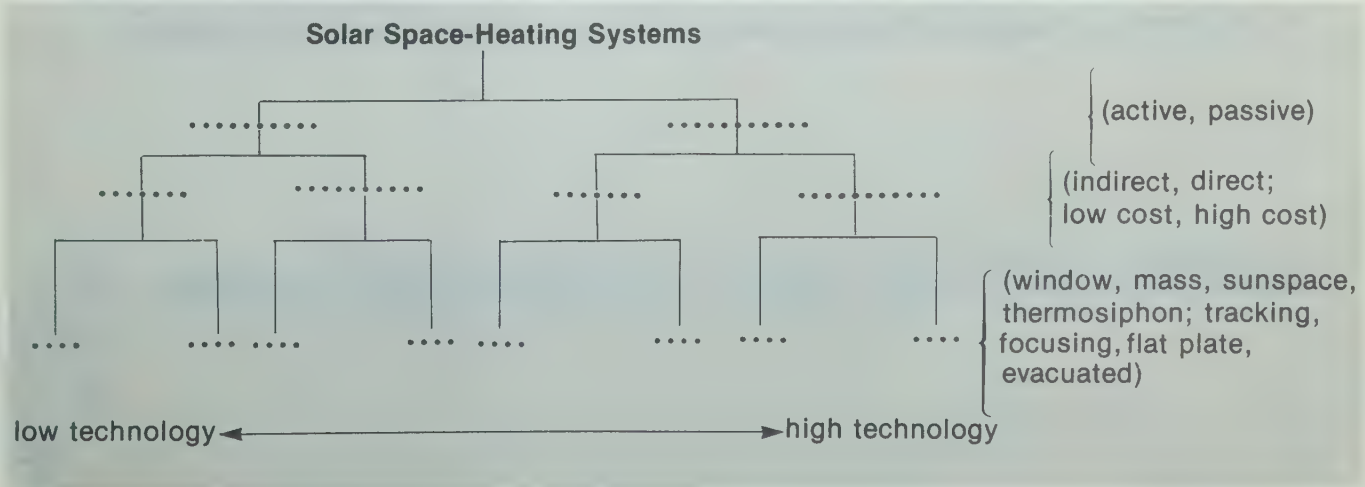
4. insulation

5. vapor barrier

6. insulated window shutters

7. thermal mass

8. Complete the following flowchart by using the words provided to the right of the flowchart. The completed flowchart should depict the lowest technology applications on the left and the highest technology application on the right.


Solar Space-Heating Systems
(active, passive)
(indirect, direct; low cost, high cost)
(window, mass, sunspace, thermosiphon; tracking, focusing, flat plate, evacuated)
low technology
high technology

9. In a passive solar home with a Trombe wall, explain how heat is transferred by conduction, convection and radiation.

10. Compare the amount of solar energy received by a 3.0 m^2 of a horizontal surface versus a vertical surface during the month of December at your location.

[*horizontal surface*] | [*vertical surface*]

11. List two important properties, other than reasonable cost, of a heat storage material.

12. What are two major advantages of water as a heat storage material as compared with rock?

13. List three advantages and three problems of Glauber's salt as a heat storage material.

14. Compare the viability of passive solar heat systems and active solar heat systems.

Note: In the following three questions calculate the local cost of the stored heat at current prices for electrical or gas heating. (Assume 1.0 ¢/MJ for electrical energy and 0.20 ¢/MJ for gas.)

15. How much solar heat is stored in a 3.00 m by 3.00 m by 2.00 m rectangular tank of water as the temperature of the water rises from 20°C to 40°C?

16. A concrete Trombe wall measures 8.00 m by 3.00 m by 28 cm thick. Calculate the heat stored in the wall as its temperature rises from 18°C to 38°C.

17. In one proposed solar heat storage system, 4.7 kg of Glauber's salt is stored in a long, rotating cylinder (See Figure 59). Calculate the amount of solar heat stored as the salt changes state.

18. What are the chief advantages of forced-air heat transport from storage as opposed to hot-water transport to heat radiators?

19. Why must the size of a water heat storage tank be carefully chosen in order that the maximum temperature of the water during sunny periods not be too high?

20. Why must the maximum temperature of a water storage tank not be too close to the room temperature desired for the house?

A North American city, Ralos City, with a continental climate, has a mean daily solar radiation for January of 13.3 MJ/(m^2.d) on a vertical south-facing surface. In Ralos City the heating cost is 0.30 ¢/MJ and an average (110 m^2) house would require 1.15 GJ/d in January. Use this information and a collector efficiency of 50% to answer the following question.

21. Calculate amount of solar energy collected per m^2 of collector per day.

22. What must the collector area be in order to supply the total daily space heating requirements of an average house for one day in January?

23. Would the collector area calculated in the previous question be practical for the average house? Explain.

24. If a rectangular solar collector 5.00 m by 10.00 m was used, what percentage of the space heating needs could be collected during a day in January?

25. Calculate the money saved on the monthy fuel bill if a 5.00 m by 10.00 m solar collector is used.

26. What volume of water must be used to store the total heat intake for one day within a temperature rise of 10°C using a 5.00 m by 10.00 m solar collector?

Optional

27. Complete the following table using local solar radiation, heating and energy cost data.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days in Month	31	28	31	30	31	30	31	31	30	31	30	31
*Mean Daily Solar Radiation ($MJ/m^2.d$))												
Collector Area (m^2)	50	50	50	50	50	50	50	50	50	50	50	50
Collector Efficiency %	50	50	50	50	50	50	50	50	50	50	50	50
Solar Energy Collected (GJ/mon)												
†Space Heating Needs (GJ/mon)												
% of Space Heating Collected												
†Cost saving ($/mon)												

*Use solar radiation data for a latitude +15° collector angle or for a vertical collector.
†Obtain the space heating needs and energy cost from your utility bills or from the local utility, or use 1.0 ¢/MJ for electrical energy and 0.20 ¢/MJ for natural gas.

28. During what portion of the year would the house be self-sufficient for space heating using solar energy?

29. What other important information is required to assess the practicality of an active solar space heating system?

30. Speculate on why the public, the media and the government have initially concentrated their attention on active solar systems.

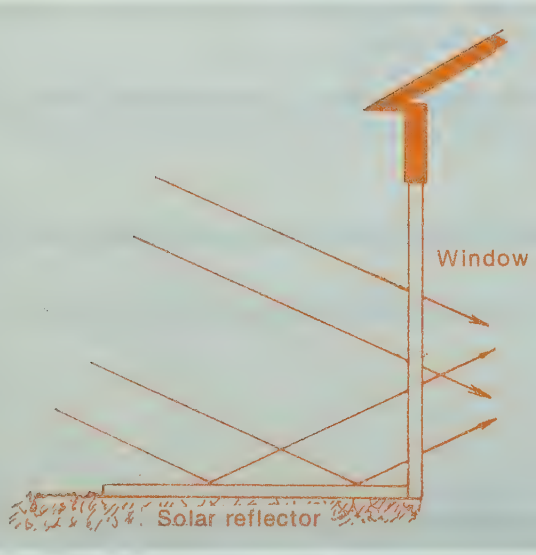
CONCENTRATING COLLECTORS INTRODUCTION—MIRRORS

Introduction

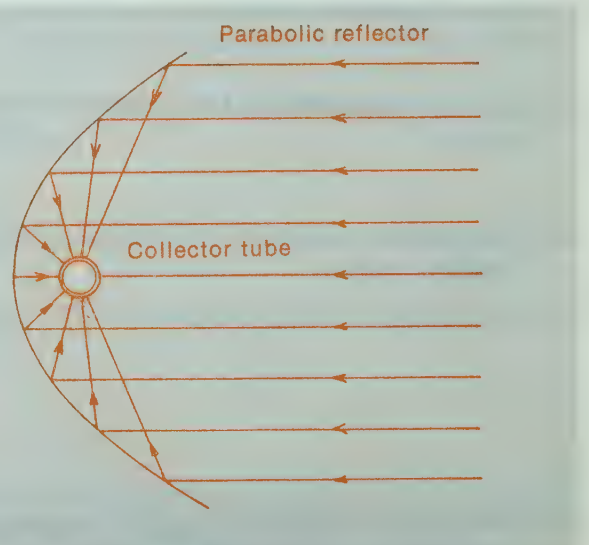
Concentrating solar collectors differ from flat plate collectors primarily in their ability to focus or concentrate the incident solar radiation. The greater intensity of solar radiation (i.e., in W/m^2) produced is achieved by use of the principles of reflection and/or refraction. Recall that when radiation strikes a surface or boundary (e.g., the atmosphere of Earth or a man-made collector), the radiation may be absorbed, reflected or transmitted. Dull dark surfaces (e.g., collector absorber plates) maximize the absorption of radiation with little reflection and no transmission. White or shiny surfaces (e.g., mirrors) maximize the reflection with little absorption and no transmission. Transparent objects with nonparallel sides (e.g., lenses) maximize the transmission with little reflection and absorption. Transmission of radiation at a boundary is almost always accompanied by a change in the direction of the radiation. This change in direction at a boundary is known as *refraction*.

Mirrors

Any shiny surface will be a reflector, but polished metal surfaces are the best reflectors. Commercial mirrors are made by coating a piece of glass with silver to obtain a smooth, shiny surface. The metal coated back is then painted for the protection of the metal surface. To concentrate solar radiation, the reflector must be smooth but may be either plane (flat) or curved. Reflection from a plane surface is used to concentrate (increase the intensity of) solar radiation incident on a large area such as a window or flat collector (see Figure 63). Because the individual rays are all reflected at the same angle from the plane surface, the degree of concentration is relatively low.



Reflection from a Plane Surface
Figure 63



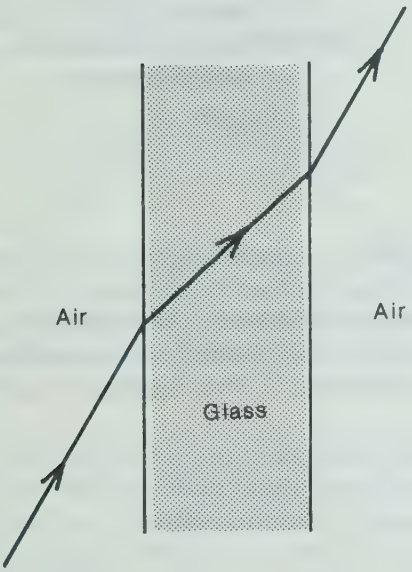
Reflection from a Curved Surface (Parabola) (Trough Collector)
Figure 64

When individual rays strike a curved surface they are reflected at different angles. A high degree of concentration of the radiation occurs at the focal point or the point where the reflected rays meet. (See Figure 64.) Spherical reflectors usually do not produce a very sharp focus, but are still useful if a large object such as a pot or pan is placed at the "focal point." For a sharper focus (necessary for concentrating solar radiation on a small object such as a copper pipe) a parabolic reflector is best.

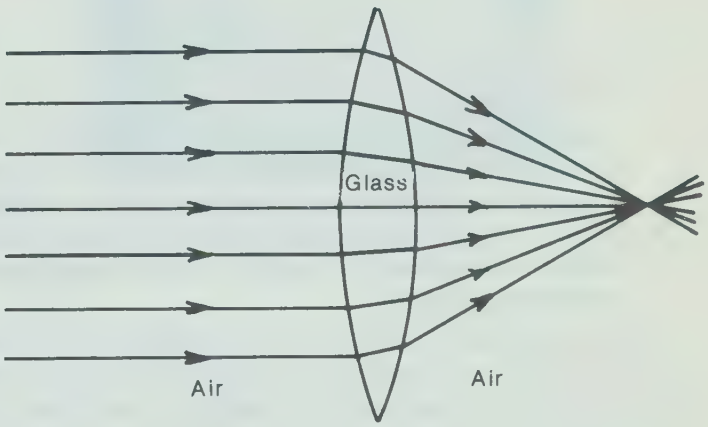
Lenses

The bent appearance of a spoon partially in a glass of water and the operation of the eye are explained by the principle of refraction. When light strikes a transparent boundary (at an angle other than 90%) its direction changes in a predictable way. The amount of bending (refraction) depends on the *relative* densities of the substances on the two sides of the boundary and on the angle of the incident radiation at the boundary.

If the boundary is a plane surface such as a window, all rays are refracted at the same angle and remain parallel (see Figure 65). A curved boundary refracts the incoming parallel rays by different amounts and the rays may be concentrated or focused (see Figure 66).



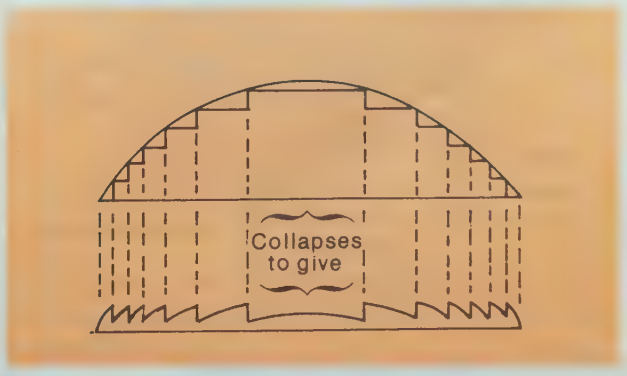
Refraction at a Plane Boundary
Figure 65



Refraction at Curved Boundaries
(Convex Lens)
Figure 66

A convex lens of any reasonable size is quite expensive. To overcome this problem a thin groved piece of plastic called a *Fresnel* lens may be used. The Fresnel lens is a good approximation of a *collapsed* plane-convex lens. Since refraction only occurs at boundaries and is independent of the thickness of the lens, the Fresnel lens maintains the boundary shape but allows for a thin lens.

Once a master disc is formed, plastic lenses can be pressed (like vinyl records) for a reasonable price. The focus is sufficiently sharp to produce temperatures up to 1000°C.

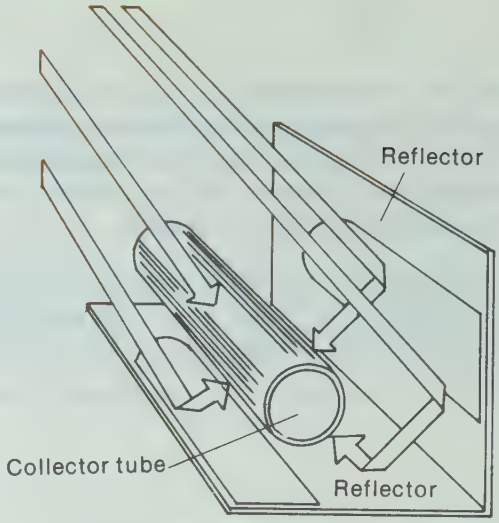


Principle of a Fresnel Lens
Figure 67

Nonfocusing Solar Concentrators

1. A Simple Solar Concentrator

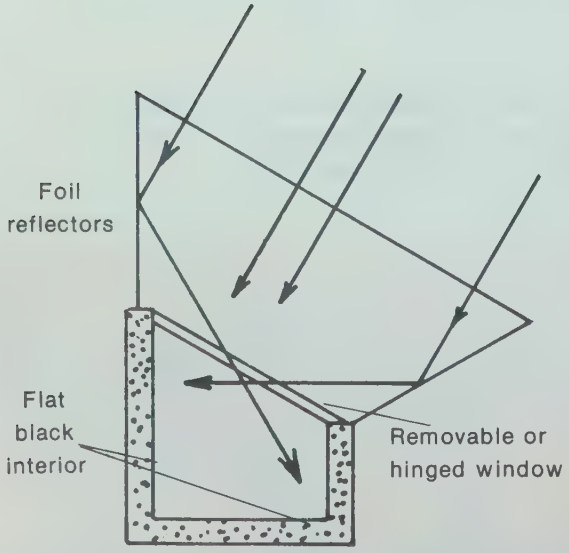
The simplest and cheapest concentrating collectors are ones that concentrate the solar energy without focusing at a point. Two perpendicular mirrors or other reflective surfaces can be used to concentrate solar energy on a collector tube (see Figure 68). Although not as efficient as a parabolic reflector, this arrangement produces approximately four times the energy concentration compared to a flat collector with no mirrors. Large angles up to 90° eliminate the need to continuously aim the collector at the sun.



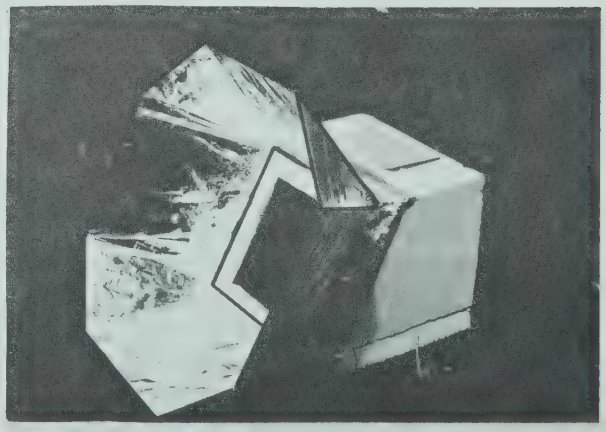
Concentrating Collector for an Active System
Figure 68

2. Solar Ovens

Solar ovens (Figure 69 and 70) also fall in the category of concentrating but nonfocusing collectors. These collectors can easily be constructed from either rigid foam insulation for support and insulation or from plywood or metal with insulation added. The reflectors are often made of sheet aluminum or covered with aluminum foil and either hinged or removable. Simple homemade ovens can easily reach temperatures of 150-200°C if the interior is sealed and painted flat black.



Solar Oven—Side View (for high solar altitude)
Figure 69



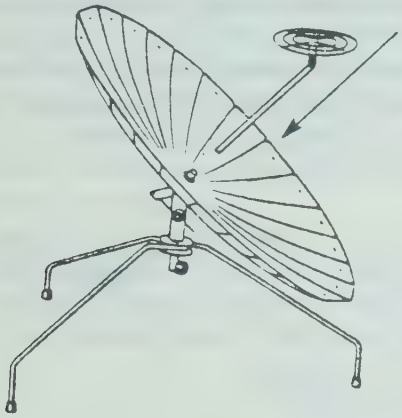
Solar Oven—Front View (for low solar altitude)
Figure 70

Focusing Solar Concentrators

The second main type of concentrating collectors are the focusing collectors. Most examples in this category use curved reflectors to concentrate the solar radiation.

1. Solar Cookers

Solar cookers, either homemade or commercial, usually use a dish reflector (see Figures 71 and 72). Since a relatively larger (dark colored) object such as a pot or pan is placed at the focal point, the collector does not have to produce a sharp focus. This type of collector usually produces temperatures of about 180°C and can boil a litre of water in about 15 min. Many commercial units are now available using a fold-away, portable, parabolic dish.

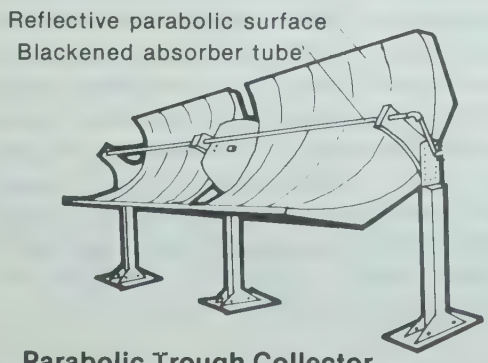


Commercial Folding Solar Cooker
Figure 71

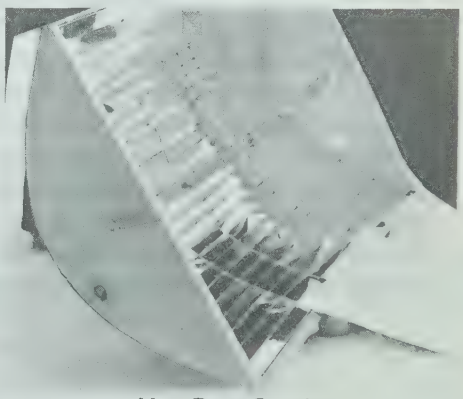
Homemade Solar Cooker
Figure 72

2. Trough Collectors

One of the most common types of concentrating collectors is the parabolic trough collector which consists of an absorber tube suspended at the focal point of the parabola (Figure 73). A simple, but effective trough collector can be made using a sheet of galvanized steel with mirror strips glued to the inner surface (see Figure 74). When parabolic troughs are used in conjunction with an active system, the entire reflector may be mounted on a moveable frame designed to follow (track) the sun's movement. Alternatively, the reflector may be stationary and the absorber moved.



Parabolic Trough Collector
Figure 73



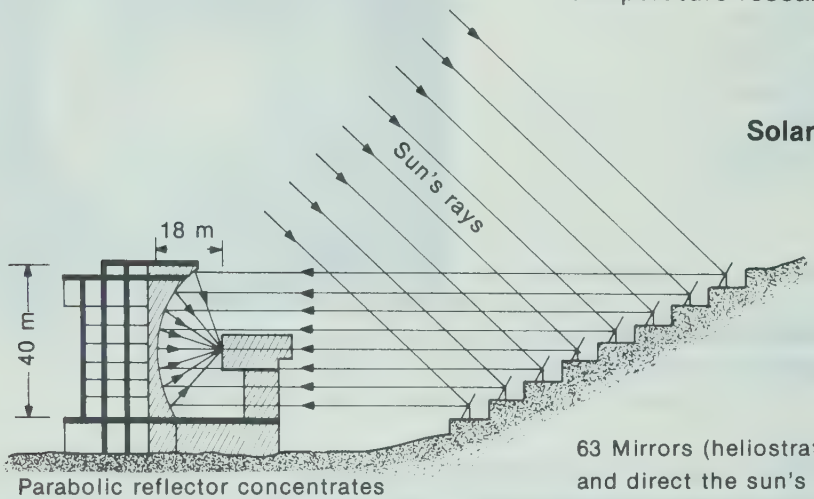
Hot Dog Cooker
Figure 74

Parabolic trough concentrators are presently being investigated for solar power-generation applications. In the Acurex Corporation system, a trough-shaped reflector about 3 m long focuses solar radiation onto a tube containing a fluid such as oil. The hot fluid from many concentrators can be used to supply heat for industry or electric power generation. A 150 kW demonstration model is operating at Coolidge, Arizona and a 500 kW power station will be built for the International Energy Agency in Almeria, Spain.

3. Solar Furnaces

A small magnifying glass (convex lens) can concentrate a surprisingly large amount of radiant heat. A small solar furnace uses the same principle as the magnifying glass on a larger scale. A plastic Fresnel lens (usually about 35 cm in diameter) is set up in an equatorial mounting which easily tracks the sun. This simple appartus can reach temperatures of 1000°C in a very short time and can be used for soldering, making jewellery and heating a kiln.

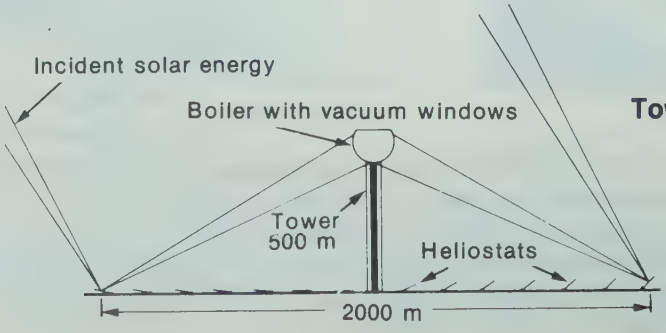
Large scale solar furnaces are now found in many countries and are used primarily for industrial research. These solar furnaces use large scale reflectors to concentrate the solar radiation. The most famous is located at Odeillo in the French Pyrenees (Figure 75). The north-facing parabolic reflecting surface contains 9000 mirrors to focus the solar radiation collected from 11 000 flat mirrors on the south facing hillside opposite the parabolic reflector. The furnace room, which is located at the focus, can in minutes produce a temperature of 3300°C for high temperature research and manufacturing.


Sun's rays
18 m
40 m
Parabolic reflector concentrates
sun's rays onto target area
63 Mirrors (heliostrates) track the sun
and direct the sun's rays into the parabolic reflector

Solar Furnace - Odeillo, France
Figure 75

4. Power Towers

The purpose of power towers is to generate electricity by vaporizing a fluid (usually water) which drives an electrical generator. The basic design involves many mirrors surrounding and focusing solar energy on a boiler at the top of a tower. The focused solar radiation vaporizes water to produce clean, reliable and efficient steam at approximately 500°C. McDonnell-Douglas has designed and is helping to build *Solar One* - the pilot plant for the U.S. government's solar energy program. Solar One, like other power tower prototypes in Italy, Spain and West Germany, is expected to produce electricity at competitive rates and also to provide a source of steam or hot water heat for residential and commercial buildings. Since higher efficiencies are possible with power tower technology compared to parabolic trough concentrators, power towers are probably best suited for larger scale solar power plants. The cheaper and less efficient parabolic trough concentrators are probably best suited for the smaller scale solar power plants.



Tower Concept for Power Generation
Figure 76

Summary of Concentrating Collectors

Concentrating collectors are either focusing or nonfocusing and the vast majority use mirrors or reflective surfaces as opposed to lenses. On a small scale, concentrating collectors, such as solar ovens and cookers, are mainly suited to solar and outdoor enthusiasts. Large scale applications, such as solar furnaces and power towers, use large reflecting surfaces for high temperature industrial research or for electric power generation.

Concentrating collectors have several advantages. In addition to the use of a free, nonpolluting and renewable energy source, they overcome one main disadvantage of solar energy - the relatively dilute form in which it arrives at the surface of Earth. Concentration of solar radiation makes solar energy more efficient and more economical than simple direct or diffuse radiation for some uses.

The main disadvantage of concentrating collectors compared to other types of collectors is the fact that they respond only to direct solar radiation. Some types of concentrating collectors also require an automatic tracking mechanism to follow the sun's movement across the sky. This added complication depends a great deal on the type and design of the collector and is not necessary for all concentrating collectors.

Like all other applications of solar energy, concentrating collectors are not meant to solve the world's energy crises. However, they do hold sufficient promise to help, along with other applications of solar energy and other energy sources, to reduce the world's dependence on fossil fuels.

Exercise:

1. List five uses for heat where temperatures higher than 90°C are either desirable or necessary.

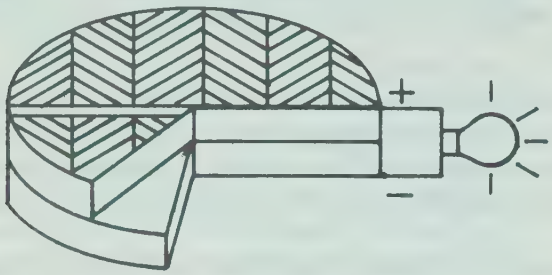
2. Sketch some possibilities for adding reflectors to solar heated homes.

3. (Optional) A certain solar reflector reflects 80% of the incident solar radiation of 600 W/m^2 to an absorber tube. 95% of the absorber radiation is converted into heat and 75% of this heat is transferred to one litre of static water in the absorber tube. Determine the time in minutes required to raise the temperature of the water from 10°C to 90°C.

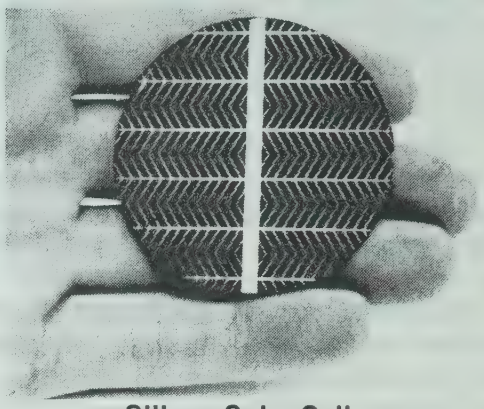
APPENDIX 3
SOLAR CELLS
INTRODUCTION TO AND OPERATION OF SOLAR CELLS

Introduction to Solar Cells

Solar cells, using the *photovoltaic* effect, convert *light* directly into *electricity*. No physical movement (except of electrical charges), no heat-to-steam step, no pollution and no noise are involved in the operation of a solar cell.



Cross Section Diagram of a Silicon Solar Cell
Figure 77

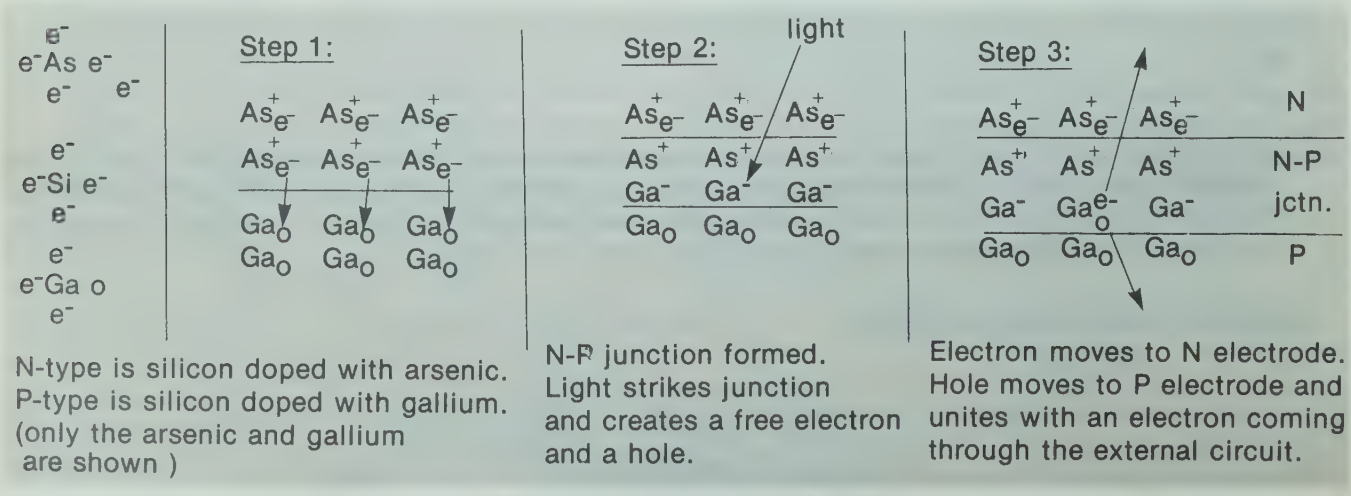


Silicon Solar Cell
Figure 78

Operation of a Silicon Solar Cell

The N-type half of the thin silicon wafer shown in Figure 77 has many electrons which do not fit into its crystal bonding. The P-type half is short of electrons to complete its crystal bonding, leaving *holes* which act like positive charges. Unbound electrons in the N-type and holes in the P-type materials are free to wander about. At the P-N junction (the surface between the two layers of materials) electrons from the N-layer fill holes from the P-layer. The holes disappear and the electrons are now bonded leaving only fixed positive charges on the N-side and fixed negative charges on the P-side (see Figure 79). Thus, a barrier is set up at the junction which reduces the passage of unbound electrons from the N-side to the P-side and also resists the movement of holes from the P-side to the N-side of the wafer.

Light photons striking the materials of the wafer increase the energy of some of the bound electrons enough to cause them to break loose from the crystal structure and become free to move, creating at the same time more positive holes. Because of the barrier at the P-N junction, electrons in the N-layer tend to move away from the barrier toward the N-electrode giving it a negative charge (see Figure 61). Similarly, holes in the P-layer tend to move to the P-electrode giving it a positive charge. The potential difference between the two electrodes can drive a current through a wire and thus produce useful electricity. The greater the number of electrons and holes created in the layers by the energy of solar radiation, the more current will tend to be produced. Silicon solar cells typically convert about 12% of the light striking them into electricity.



Operation of a Silicon Solar Cell
Figure 79

APPENDIX 2
SOLAR CELLS
ADVANTAGES AND DISADVANTAGES AND STORAGE SYSTEMS

Advantages of Solar Cells

With respect to energy sources in general, solar cells have some distinct advantages.

1. Solar cells use a free energy supply.
2. Solar cells require little maintenance.
3. Solar cells have a long useful lifetime.
4. Solar cells are nonpolluting.
5. Solar cells have a simple structure which can be mass produced.
6. Solar cells permit a decentralized power supply.

Disadvantages of Solar Cells

With respect to energy sources in general, solar cells have some distinct disadvantages.

1. Solar cells are low in efficiency.
2. Operation of solar cells is limited to daylight hours. Energy storage systems are needed for most uses.
3. Capital cost of solar cells is high and their production uses a large amount of energy.
4. Solar cells produce direct current which must be converted to alternating current if it is to be efficiently transported over power lines.
5. Solar cells individually yield a low voltage which must be increased by special measures for most uses.

Energy Storage Systems

Several storage methods can be used for the electrical output from solar cells on ground installations or orbiting satelites.

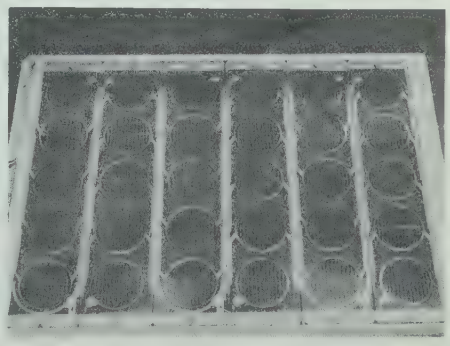
1. Batteries can be charged by solar cells to provide portable energy that is convenient to use. Present batteries are costly and massive in proportion to the energy they store but recent research has led to development of high-energy-density, efficient batteries.

2. Water can be pumped by solar cell powered pumps to a high storage reservoir when solar cell energy is not needed. When electrical power is needed the water flows through a turbine to drive a generator to produce electrical power.

3. Hydrogen and oxygen gas can be produced by the electrolysis of water using the electricity from solar cells. Hydrogen gas is a clean high temperature fuel which could replace all present fuels.

Solar Assisted Wristwatch
Figure 80

Solar Assisted Automobile
Figure 81



Solar Cell Bank
Figure 82

RECENT ADVANCES AND OVERVIEW OF SOLAR CELLS

Recent Advances in Solar Cell Technology

Dramatic advances in improved efficiency have been made since solar cells were first developed. In 1953 solar cell efficiency was thought to be limited to about 1%, but by 1959 efficiencies higher than 5% were readily attained. Now, efficiencies better than 12% are common and attainment of nearly 20% efficiency is thought to be possible by 1985.

Equally dramatic have been manufacturing cost reductions. Early development costs were extremely high and hard to assess. By 1959 capital cost for solar cells was about $200/W (of peak output). Since then the cost has fallen to less than $20/W and may be as low as $0.50/W for silicon solar cells by 1985. The secret of success seems to lie in finding a low cost method of growing crystalline silicon.

Very recently, investigation into the possibility of developing amorphous (random atomic structure) solar cells has intensified. Several companies have done extensive research on amorphous solar cells in view of the prospect of costs as low as $0.05/W ultimately.

SOLAR CELLS
OVERVIEW

Overview Exercise:

1. List four advantages of solar cells as an energy source.

2. Explain how the silicon solar cell works.

3. List three disadvantages of solar cells as they now exist.

4. What is the power output from rectangular bank of solar cells 2.0 m by 3.0 m when the solar radiation is 0.60 kW/m^2? (Assume the cells are 11% efficient and a recent square design.)

5. List three methods for storing electrical energy from solar cells. Can you think of any original storage methods?

APPENDIX 3
STUDENT SOLAR PROJECTS

Purpose:

1. To construct a solar apparatus.
2. To describe how the constructed solar apparatus works.
3. To display and use the solar apparatus.

Procedure:

1. Use a list of library references, any project plans distributed and/or ideas from this solar energy elective unit to select a project to build. Record the date and the name of the project on the classroom project sheet.
2. Prepare a brief (one page) description of the solar project including a list of materials and a diagram of the apparatus. Show the description to the teacher at least two weeks before the scheduled completion date.
3. Build the solar apparatus at home. Unless the intention is to use the apparatus following the display, use inexpensive materials such as aluminum foil and cardboard.
4. Test the apparatus at home and collect data if appropriate. Make any necessary adjustments to the solar apparatus.
5. Prepare to answer any questions as to how the solar apparatus is supposed to work, does work or does not work. Questions will be asked by the teacher.
6. Bring the solar apparatus and any food to be cooked on the day of the display. Make sure that all equipment is obtained before the display.
7. Use a 10 cm x 15 cm card to label the apparatus with a title of what the apparatus is, a couple of pieces of significant data, and the name of the builder.

Evaluation:

The evaluation of the apparatus will be based on the following aspects:

a. construction — amount of time spent and quality and creativity of work
b. explanation — an oral explanation of the solar principles involved in the project
c. a written test on your project category

The percentage of the mark on *construction* and *explanation* will depend upon the particular project. For example, a project which required little construction time might be marked 30% on construction and 70% on explanation. The time spent on the project is equalized for all students in this way.

Appendix 3
STUDENT SOLAR PROJECTS

Some Suggested Solar Projects

Category A: Solar Home Models

1. Low energy passive solar homes
2. Standard passive solar homes
3. Active and passive solar homes
4. Retrofitted solar homes
5. Experimental windows and/or shutters
6. Trombe or drum wall model
7. Solar landscaping model
8. Air-to-air heat exchanger
9. Solar doghouse
10. Insulation principles demonstrator
11. Air infiltration principles demonstrator

Category B: Flat Plate Collectors

1. Water collectors
2. Air collectors
3. Food or grain dryers
4. Solar principles demonstrator
5. Solar cooling demonstrator

Category C: Solar Greenhouses and Stills

1. Solar greenhouse model (freestanding)
2. Integrated solar greenhouse
3. Solar still
4. Solar plant grower

Category D: Concentrating Collectors

1. Solar ovens
2. Parabolic cooker
3. Lenses
4. Solar hot dog cooker
5. Solar furnace model
6. Solar power tower model

Category E: Solar Cells and Radiometers

1. Solar powered model airplane
2. Solar powered model car
3. Solar powered radio
4. Solar battery charger
5. Thermopile radiometer
6. Solar cell radiometer

Solar Home and Greenhouse Models
Figure 83

Solar Ovens
Figure 84

Flat Plate Water Collector
Figure 85

APPENDIX 4
STUDENT REFERENCES

Anderson, Bruce. The Solar Home Book, Cheshire Books, Harrisville, New Hampshire, 1976. An informative easy to read introduction to the use of solar energy in the home. Very well illustrated. Extensive data tables. U.S.A. climatic data. Nonmetric. 300 pages.

Daniels, Farrington. Direct Use of the Sun's Energy. Ballantine Books of Canada Ltd., Toronto, 1964. Paperback. Comprehensive, thorough, authoritative and clearly written. A classic. Still an excellent general reference. 271 pages.

Halacy, D.S.Jr. Solar Science Projects for a Cleaner Environment. Scholastic Book Services, New York, 1974. Paperback. Provides specific directions for seven reasonably low budget solar projects in simple nontechnical language. 96 pages. (Also see Experiments with Solar Energy by D.S. Halacy.)

Lyons, Stephen (ed). Sun! A Handbook for the Solar Decade. Friends of the Earth, San Francisco, 1978. Comprehensive. More for general background than for specific guidance. 365 pages.

Mazria, Edward. The Passive Solar Energy Book. Rodale Press, Emmaus, Pennsylvania, 1979. A complete guide to passive solar home, greenhouse and building design. Underlying principles of systems described are discussed. Very well illustrated. Many useful charts and tables. Nonmetric. Canadian and U.S.A. climatic data. 435 pages.

Popular Science. Times Mirror Magazine Inc., 380 Madison Avenue, New York. 10017. A monthly magazine with an energy news section that presents what is new in the solar energy field in well illustrated easy-to-read articles.

Sol. Solar Energy Society of Canada Inc. 608 - 870 Cambridge Street, Winnipeg, Manitoba. R3M 3H5. A newsletter published about six times a year to keep members of the Society up to date on solar energy affairs in Canada in particular, with some mention of solar energy activities in other countries.

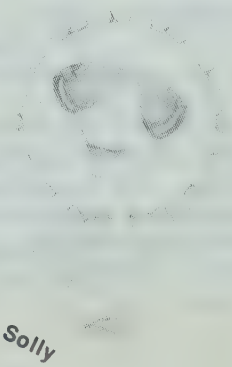
Solar Energy Handbook. Published by Popular Science, 1979. A sourcebook covering many aspects of the practical application of solar energy by homeowners. Well illustrated. Contains an extensive buyers guide for the U.S.A. 112 pages.

Solar Heating Catalogue No. 2. Energy, Mines and Resources Canada, 1978. Conservation and Renewable Energy Resources Branch, 580 Booth Street, Ottawa. K1A 0E4. Provides a list of solar heating services and products available at specified places in Canada. Price, $2.00 in Canada.

Solwest. Solar Energy Society of Canada Inc., 504 Davie Street, Vancouver, B.C. V6B 2G4. A monthly newsletter published by western chapters of the Solar Energy Society of Canada. Distributed to chapter members. (Join or start your own local chapter of the national Solar Energy Society.)

Sunset Homeowner's Guide to Solar Heating. Lane Publishing Co., Menlo Park, California, 1978. Describes features of both active and passive home heating systems. Many good diagrams and pictures but very limited mathematical support of ideas discussed. 96 pages.

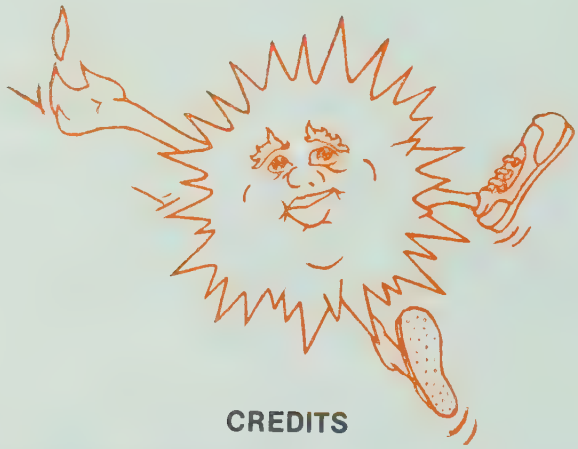
Note:
A more complete list of solar energy references may be found in the bibliographies of the above listed references or in the teachers' guide which accompanies this book.



absorber - the dark surface of a collector that absorbs the solar radiation and converts it to heat energy
absorptance (absorptivity) - the ratio of solar energy absorbed by a surface to the solar energy striking it
active solar system - a solar heating or cooling system that requires pumps, fans, etc. to transfer the heat collected or stored
air collector - a solar collector using air as the heat transfer fluid
ambient temperature - the temperature of the air surrounding a solar collector or heat storage bin
amortization - the process of repaying a sum of money plus interest over a fixed period of time
auxiliary heat - the extra heat provided by a conventional heating system to supplement the output provided by the solar heating system
berm - a natural or man-made mound of earth
caulking - making an airtight seal by filling in cracks (e.g., around windows and doors)
clerestory - a window placed vertically in a second story wall to admit solar radiation into a building
collector efficiency - the ratio of heat energy obtained from a collector to the solar energy striking the cover
conduction - the transfer of heat energy through a substance by collisions of adjacent ions, atoms or molecules
convection - the transfer of heat energy from one location to another by the motion of fluids (gases or liquids)
desiccant - a chemical which removes water, thereby drying another substance such as air
direct gain - solar radiation which enters directly into a living space through a window
diffuse radiation - solar radiation that is scattered by particles (molecules, dust and clouds) and travels an indirect path to a surface
direct radiation - solar radiation that travels a direct path to a surface
drum wall - a passive solar collector and heat storage unit comprised of darkened drums containing water
efficiency of a solar cell - the ratio of the electrical energy output of the solar cell to the energy of the solar radiation falling on its surface
electromagnetic radiation - any radiation made up of oscillating electric and magnetic fields (e.g., UV, visible, IR)
emittance (emissivity) - a measure of the tendency of a material to emit radiation
ethylene glycol - a common alcohol antifreeze having the chemical formula, $C_2H_4(OH)_2$
eutectic salt - a hydrated salt that absorbs or releases large amounts of heat as it melts or solidifies (e.g., $Na_2SO_4.10H_20_{(s)}$)
flat-plate collector - a solar collector that converts solar radiation into heat energy on a plane, dark surface
geosynchronous satellite - an artificial satellite in orbut about 36 000 km from Earth such that it remains continuously above the same spot on Earth
Glauber's salt - sodium sulfate decahydrate ($Na_2SO_4.10H_2O$), a common eutectic salt with a low melting (dehydration) point of 32°C
glazing - a transparent or translucent glass or plastic covering (e.g., a window pane)
glazing transmission coefficient - the fraction of (perpendicular) solar radiation transmitted through a particular glazing
greenhouse effect - is due to the characteristics of some transparent materials which transmit shortwave IR radiation and block IR radiation at longer wavelengths and block convection currents. In an enclosure the longer wavelength IR radiation comes primarily from the heated objects and this radiation along with the thermal heat is trapped inside
heat capacity - the quantity of heat required to raise the temperature of a body one degree Celsius
heat engine - a device for converting heat into mechanical energy
heat exchanger - a device used to transfer (exchange) heat from one body of fluid to another usually through a thin (metal or plastic) conducting wall
heat pump - a mechanical device that transfers heat from one place to another (using a refrigerant transfer fluid)
hybrid system - a solar energy heating or cooling system specifically designed to include both active and passive systems
infiltration - the uncontrolled movement of outdoor air into a building though cracks around windows and doors or in walls and ceilings; a source of major heat loss
insolation - the total solar radiation (direct, diffuse and reflected) striking a surface
insulation - materials or systems with high thermal resistance (*R*) used to prevent loss or gain of heat

isohel - a line on a map connecting points receiving equal amounts of sunshine
integrated greenhouse - a greenhouse planned and built into a house at the same time the house is planned and built. This enables the arrangement of an efficient and generally pleasing living unit
latent heat of fusion - the heat stored or released as a substance melts or solidifies, (respectively). (The temperature of the substance remains constant.)
liquid collector - a solar collector using a liquid (usually water or a water-antifreeze mixture) as the heat transfer fluid
mean - average (obtained by adding quantities together and dividing by the number of quantities)
microwave - a part of the electromagnetic spectrum used extensively in communication systems and thought to be a possible means of long distance energy transmission (e.g., from solar cells in synchronous orbit)
n-type silicon - silicon crystals containing an impurity such as arsenic which provides the crystal with extra electrons
nuclear fusion - a type of nuclear reaction in which light nuclei combine to form heavier nuclei. A small amount of mass is converted into a large amount of energy.
ozone - a very reactive and poisonous form of oxygen with a chemical formula, O_3. There is a narrow band of ozone high in the atmosphere.
passive solar system - a solar heating or cooling system that uses no external mechanical power to collect, store and transfer heat
photosynthesis - the conversion of solar energy into chemical energy by the green chlorophyll in plants
photovoltaic cell - a semi-conductor device that converts electromagnetic radiation into electricity (e.g., a solar cell)
p-n junction - the boundary between p-type and n-type silicon crystals (e.g., in solar cells)
p-type silicon - silicon crystals containing an impurity such as aluminum which creates a crystal with electron deficiencies (holes)
radiation - the transfer of energy (e.g., heat) from one location to another by means of electromagnetic waves (e.g., IR radiation)
refraction - the changing of the direction of light when it goes at an oblique angle from one medium into another (in which it has a different velocity)
retrofitting - the addition of solar heating or cooling systems to an existing building
***R*-value** - a unit of thermal resistance equal to the reciprocal of the thermal conductance. *R*-value is used to compare insulating values of different substances.
selective coating or surface - special paints or chemicals which optimize the absorptance and minimize the emittance of a solar collector surface
Sol - the astronomical name of our sun
solar altitude - the vertical angle of the sun above the horizon
solar azimuth - the horizontal angle of the sun measured east or west from true south (0°)
solar cell - a photovoltaic cell used to convert solar energy directly into electrical energy
solar cell array - an orderly arrangement of a large number of solar cells set up so as to maximize receipt of solar energy
solar collector - a device used to capture solar energy - ranging from an ordinary window to a complex mechanical device
solar constant - the power from the sun per square metre perpendicularly reaching Earth's atmosphere (approximately 1.4 kW/m^2)
solar electric automobile - a battery powered automobile whose batteries are charged by using solar cells
solar furnace - a furnace designed for high temperature operations that uses sunlight concentrated by means of an array of mirrors fucussed on the same spot
solar radiation (energy) - the electromagnetic radiation emitted by the sun
specific heat capacity - the quantity of heat required to raise the temperature of one kilogram of material one degree Celsius (kJ/kg.°C)
sun path chart or diagram - a graph of solar altitude versus solar azimuth showing the position of the sun from sunrise to sunset for the 21st day of each month
therm - a unit of heat energy equal to 1000 000 Btu or 105.5 MJ
thermal conductivity - the thermal conductance of a one metre thick slab of material (W/(m.°C))
thermal heat - the heat stored as a result of a temperature rise in a material
thermal mass - the potential heat storage capacity available in a building or system. Thermal mass often refers specifically to Trombe walls, drum walls, concrete floors, etc., but does include all mass in a building or system.

thermal storage - the storage of heat as thermal heat (temperature rise) as opposed to latent heat (no temperature rise)
thermal resistance - the tendency of a material to retard the flow of heat (see *R*-value)
thermosiphon - the natural movement of heat in a system by convection of a fluid (also called thermocirculation, gravity convection)
tilt angle - the angle that a flat solar collector surface makes with the horizontal
total energy system - a system for providing all the energy requirements of a unit such as a residence, a business, or a community
trickle collector - a solar collector in which the heat transfer liquid flows (usually in channels) down the face of the absorber
Trombe wall - a wall with a high thermal mass located inside a building near a large glazed exterior wall so as to store heat received during sunny periods and release it when the sun is not shining. The Trombe wall is an indirect gain system which is usually vented at the top and bottom so as to create a thermosiphon.
turbogenerator - a combination consisting of an electric generator (dynamo) coupled with a fluid propelled turbine which drives the generator
void - the total air space between rocks expressed as a percentage of the total volume of a rock heat storage bin
volumetric heat capacity - the quantity of heat required to raise the temperature of one cubic metre of meterial one degree Celsius ($kJ/(m^3.°C)$)
weather stripping - narrow strips of thin metal or wood combined with rubber or foam to prevent **infiltration of air** around windows and doors



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Ann Arbor Science Publication Inc.: Figures 75 and 76
Davis Publications: Figure 62
Energy, Mines and Resources, Canada:Figures 45, 47, 50, 60, 61, 71 and 73. Page 36
Grumman Energy Systems, Inc.: Figure 51
Lord and Burnham Co., Limited: Figure 21
Ministry of Energy, Ontario Government: Figure 20
National Solar Heating and Cooling Information Center: Figure 28 and 38
New Mexico Solar Energy Association: Figures 22, 23a, 23b, 26 and 37
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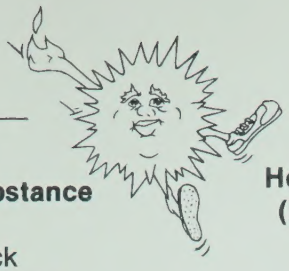


SOLAR ENERGY DATA SHEET

Substance	Specific Heat Capacity (kJ/(kg.°C))	Density (Mg/m^3)	Volumetric Heat Capacity (MJ/(m^3.°C))	Specific Latent Heat of Fusion (kJ/kg)	Volumetric Latent Heat of Fusion (MJ/m^3)
brick	0.84	2.24	1.9	——	——
concrete	0.92	2.31	2.1	——	——
ethylene glycol (50%)	3.5	1.05	3.7	——	——
wood (avg.)	2.0	0.50	1.0		
Glauber's salt	——	1.46	——	242	353
nonadecane	——	0.778	——	171	133
rock	0.86	2.24	1.92	——	——
sand	0.80	1.52	1.22	——	——
water	4.19	1.00	4.19	——	——

Glazing Transmission Coefficient

Material	Single Sheet	Double Sheet
glass	0.90	0.81
fibreglass	0.75	0.56
Mylar	0.85	0.72
polyethylene	0.92	0.85
plexiglass	0.85	0.72

SI Metric Prefixes

giga	G	10^9
mega	M	10^6
kilo	k	10^3
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

SI Metric Units & Symbols

metre	m	second	s
gram	g	minute	min
tonne	t	hour	h
litre	L	day	d
degree Celsius	°C	week	wk
joule	J	month	mon
watt	W	year	a

English and Old Metric to SI Metric

(for converting old data to SI Metric)

1 inch	=	2.54 cm
1 ft	=	0.3048 m
1 ft^2	=	0.0929 m^2
1 ft^3	=	0.0283 m^3
1 gal (U.S.)	=	3.785 L
1 gal (Imp.)	=	4.546 L
1 lb	=	0.4536 kg
1 kW.h	=	3.6 J (exactly)
1 cal	=	4.19 J
1 Btu	=	1055 J
1 therm	=	105.5 MJ
1 Btu/h	=	0.2931 W
1 horsepower	=	745.7 W
1 Btu/(ft^2.d)	=	0.01136 MJ/(m^2.d)
1 Langley	=	41.8 kJ/m^2
*R*1.00 (ft^2.°F.h/Btu)	=	*RSI* 0.176(m^2.°C/W)
1 F°	=	5/9 °C (exactly)
5/9 (°F-32)	=	°C
1 mil (1 milliinch)	=	25 μm

SI Metric Equivalents

1 W = 1 J/s (exactly)
1 t = 1000 kg (exactly)
1 cm^3 = 1 mL (exactly)
1 g/mL = 1 Mg/m^3

Miscellaneous

speed of light	=	3.00 x 10^8 m/s
Earth radius	=	6.37 x 10^3 km
Sun-Earth distance	=	1.50 x 10^8 km

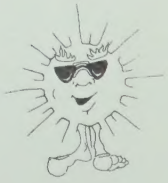
Approximate RSI Value Per Centimetre

Material	*RSI*/ cm
cellulose fibre	0.25
fibreglass batts	0.24
wood shavings	0.17
urea formaldehyde foam	0.17
vermiculite	0.16
polyurethane foam	0.3
polystyrene sheets (blue)	0.33
polystyrene sheets (white)	0.27
wood (soft)	0.087
concrete	0.005
brick	0.007

Approximate RSI Value for a Given Thickness

outside air film	0.03
wood siding	0.14
plywood sheathing (1 cm)	0.08
fibreglass insulation (9 cm)	1.95
gypsum board (1.3 cm)	0.08
inside air film	0.12
Total of wall above (assuming no air infiltration)	2.40

solid core wood door (3.8 cm)	0.36
single pane glass	0.16
double glazed (0.6 cm air)	0.30
double glazed (1.2 cm air)	0.35
carpet with rubber pad	0.21
floor tiles	0.008
hardwood flooring (1.9 cm)	0.12



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SOLAR ENERGY DATA SHEET

B40426

Monthly Mean Daily Values of Solar Radiation Incident on a Vertical South-facing Surface (MJ/(m^2.d))

Location	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vancouver, B.C.	49°	5.0	8.3	10.8	11.5	11.8	10.8	12.0	12.6	13.1	9.6	5.7	4.1
Edmonton, Alta.	54°	10.2	14.1	17.3	15.7	13.0	11.9	13.0	13.6	13.8	13.3	10.0	7.9
Suffield, Alta.	50°	12.6	16.0	18.0	14.5	12.5	11.7	13.2	14.4	14.8	14.6	11.3	10.7
Swift Current, Sask.	50°	13.0	16.6	18.8	14.5	12.3	11.4	12.9	14.0	14.7	15.0	11.6	10.7
Churchill, Man.	59°	9.12	14.6	20.9	21.2	15.2	13.5	13.4	13.3	10.5	7.5	6.9	7.5
Winnipeg, Man.	50°	13.3	17.2	18.1	14.2	12.0	11.4	12.1	13.2	13.3	11.9	9.0	10.0
Ottawa, Ont.	45°	10.5	14.4	15.3	11.9	10.5	9.8	10.3	11.3	11.7	10.7	7.0	8.0
Toronto, Ont.	44°	10.9	13.3	13.5	12.3	9.8	9.4	10.2	11.3	11.9	10.9	6.7	7.6
Montreal, Que.	45°	9.9	13.1	12.9	11.2	9.8	9.5	10.3	10.6	11.6	10.4	7.2	7.2
[illegible]cton, N.B.	46°	10.8	14.0	13.5	11.1	9.7	9.7	9.7	10.9	11.5	10.8	7.7	8.3
[illegible], N.S.	45°	8.8	11.2	12.4	10.2	9.1	9.3	9.3	10.8	11.9	11.1	8.0	6.3

Monthly Mean Daily Values of Solar Radiation Incident on a Horizontal Surface (MJ/(m^2.d))

Location	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Vancouver, B.C.	49°	2.9	5.7	10.0	14.9	20.5	21.6	23.0	18.6	13.4	7.3	3.5	2.3
Edmonton, Alta.	54°	3.7	7.1	12.5	17.5	20.6	22.0	22.6	18.3	12.7	7.8	4.0	2.6
Suffield, Alta.	50°	4.9	8.6	14.0	17.9	21.5	23.5	25.0	20.6	14.5	9.3	5.1	3.8
Swift Current, Sask.	50°	5.1	8.8	14.4	17.7	21.3	23.0	24.6	20.3	14.4	9.5	5.2	3.9
Churchill, Man.	59°	2.3	5.8	12.4	19.4	20.9	22.2	20.7	16.0	9.2	4.3	2.3	1.6
Winnipeg, Man.	50°	5.3	9.2	14.1	17.4	20.8	23.0	22.9	19.2	13.4	8.2	4.6	3.8
Ottawa, Ont.	45°	5.8	9.4	13.8	16.7	19.9	21.5	21.4	18.2	13.4	8.7	4.7	4.4
Toronto, Ont.	44°	6.1	9.1	12.9	17.7	19.4	20.9	22.3	19.0	14.1	9.1	4.6	4.3
Montreal, Que.	45°	5.3	8.7	12.5	15.8	18.5	20.7	21.2	17.2	13.2	8.3	4.5	3.8
Fredericton, N.B.	46°	5.5	8.9	12.6	15.7	17.9	20.6	19.6	17.4	13.1	8.6	4.9	4.1
Halifax, N.S.	45°	5.1	8.0	12.2	14.7	17.0	20.1	19.0	17.7	13.8	9.1	5.3	3.7

Monthly Mean Daily Values of Solar Radiation Incident on a Horizontal Surface (MJ/(m^2.d))

[illegible]ion	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
[illegible]ta, Ga.	34°	9.6	12.3	16.2	20.5	29.7	25.8	25.8	21.6	17.3	14.7	11.3	8.5
[illegible]ark, N.Dak.	47°	6.7	10.6	15.1	18.9	23.4	24.7	26.2	21.9	16.4	11.6	6.8	5.3
[illegible]n, Mass.	42°	5.7	8.4	12.1	15.4	20.1	21.2	21.1	17.8	14.4	10.2	6.1	5.0
[illegible]land, Ohio	41°	5.3	7.7	13.7	16.4	21.9	23.9	23.8	20.9	16.0	11.3	6.0	4.9
[illegible]Lansing, Mich.	43°	4.8	8.4	12.3	14.2	19.7	21.7	21.4	18.5	14.8	10.1	5.4	4.3
[illegible]anks, Alaska	65°	0.1	3.2	9.8	16.8	20.5	22.4	19.3	14.2	7.9	3.7	0.01	0.0
[illegible]Worth, Texas	33°	10.6	13.6	18.1	20.8	23.9	27.8	26.0	25.2	21.4	16.8	13.1	10.4
Great Falls, Mont.	47°	6.0	9.8	15.6	18.4	22.4	24.8	27.0	22.6	17.4	11.2	6.5	4.7
Little Rock, Ark.	35°	8.0	11.1	15.2	19.0	22.3	23.8	23.6	22.0	18.6	14.6	10.4	8.0
Las Vegas, Nev.	36°	11.8	16.3	21.8	26.4	29.9	31.8	28.7	26.6	23.4	18.2	13.5	11.0
Los Angeles, Calif.	34°	10.4	13.9	18.6	21.2	23.4	25.7	27.5	25.0	21.5	15.5	12.0	10.0
Madison, Wis.	43°	6.4	9.2	14.0	16.5	19.8	23.0	23.2	19.8	16.4	11.3	6.3	5.6
Miami, Fla.	26°	14.7	17.7	20.8	23.0	23.5	22.6	22.6	21.5	18.7	16.3	15.0	13.4
Nashville, Tenn.	36°	6.7	10.3	14.2	18.9	22.7	24.4	23.6	21.2	18.2	13.9	9.3	6.8
New York, N.Y.	41°	6.1	9.0	13.4	16.2	19.7	22.6	22.0	18.2	15.3	11.1	6.8	5.4
Phoenix, Ariz.	33°	12.8	17.2	22.3	27.1	30.8	31.6	27.8	26.1	24.2	19.2	14.6	11.8
Seattle, Wash.	48°	3.2	5.9	11.3	17.1	21.4	21.7	24.0	19.0	13.8	8.2	4.4	2.7
Washington, D.C.	39°	7.2	10.2	14.2	18.2	21.0	23.6	21.9	19.4	16.4	12.3	8.7	6.7

Monthly Mean Daily Values of Solar Radiation Incident on a Vertical South-facing Surface (MJ/(m^2.d))

Location	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Atlanta, Ga.	34°	14.6	14.8	13.1	10.5	10.9	9.1	9.1	9.5	11.4	14.7	15.8	13.5
Bismark, N.Dak.	47°	14.8	19.0	19.1	15.8	13.8	12.0	13.5	15.1	17.4	17.9	13.8	12.2
Boston, Mass.	42°	10.9	13.9	14.0	10.6	10.0	9.0	9.3	10.4	12.7	13.5	10.8	10.0
Cleveland, Ohio	41°	9.8	11.5	14.1	10.9	10.6	9.8	10.1	11.6	13.4	14.5	10.2	9.6
East Lansing, Mich.	43°	9.5	13.2	13.6	10.2	10.1	9.6	9.8	11.1	13.5	13.8	9.8	8.9
Fairbanks, Alaska	65°	3.2	8.7	19.6	20.2	17.8	19.8	19.6	20.0	13.5	8.7	3.0	0.0
Fort Worth, Texas	33°	15.5	15.6	14.1	10.4	8.8	9.4	9.2	10.4	13.5	16.4	17.7	16.0
Great Falls, Mont.	47°	13.2	17.5	19.7	15.4	13.2	12.0	13.9	15.6	18.4	17.2	13.2	10.8
Little Rock, Ark.	35°	12.5	13.9	12.7	10.3	8.9	8.7	8.7	10.0	12.6	15.5	14.8	13.3
Las Vegas, Nev.	36°	19.0	20.8	18.9	14.7	11.9	11.7	10.5	12.5	16.5	19.8	20.0	18.5
Los Angeles, Calif.	34°	15.9	16.8	15.0	10.9	8.6	9.1	9.7	11.0	14.2	15.5	16.8	15.8
Madison, Wis.	43°	12.6	14.5	15.4	11.9	10.2	10.1	10.6	11.9	14.9	15.4	11.5	11.6
Miami, Fla.	26°	17.3	15.6	12.5	8.8	7.3	6.6	6.6	7.0	9.1	12.7	16.0	16.7
Nashville, Tenn.	36°	10.8	13.2	12.4	10.6	9.0	9.0	8.7	10.0	12.8	15.1	13.8	11.5
New York, N.Y.	41°	11.3	13.5	13.8	10.7	9.6	9.3	9.4	10.2	12.8	14.2	11.6	10.6
Phoenix, Ariz.	33°	18.8	19.7	17.4	13.5	11.3	10.9	9.8	10.7	15.3	18.6	19.7	18.2
Seattle, Wash.	48°	7.2	10.8	14.6	14.8	13.2	11.2	13.0	13.7	15.0	13.8	9.2	6.4
Washington, D.C.	39°	12.7	14.2	13.8	11.5	9.3	9.0	8.7	10.0	13.0	14.8	14.0	12.3

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